PSCAD

Applications of PSCAD for Renewable Integration – Dynamic Response and Control Interactions

Presented by: Dharshana Muthumuni

Manitoba HYDRO INTERNATIONAL

Outline

Electromagnetic Transient simulation plays an important role during integration of wind and other renewable energy based generation to transmission networks. This is mostly in view of the fact that renewable generation is connected to grids through power electronic inverters.

Outline

General Description of Challenges

- Inverter based interface to power systems
- Brief Introduction to different wind turbine generator technologies
- A brief introduction to Inverters and invert controls
- Impact of transmission network characteristics
  - Connecting to weak grid locations
- EMT Studies – Background and the need for EMT studied

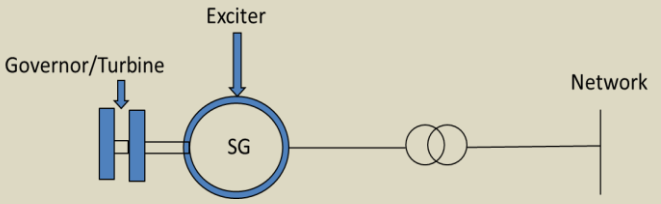
Brief Description of Selected Practical Cases (USA, UK and Australia)

- Low inertia concerns - South Australian Blackout 2016
- (Control) Interaction Issues
- Low frequency voltage oscillations
- Resonance issues and inverter response to network voltage and current transients
- Controls interactions and Torsional interaction (SSTI) concerns

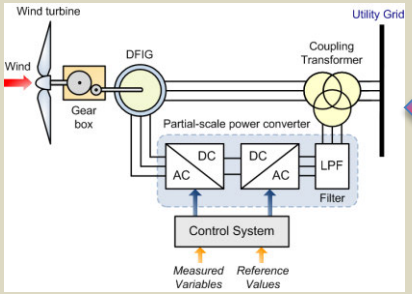
PSCAD simulation examples

Wind Generators and Influence of Transmission System Characteristics

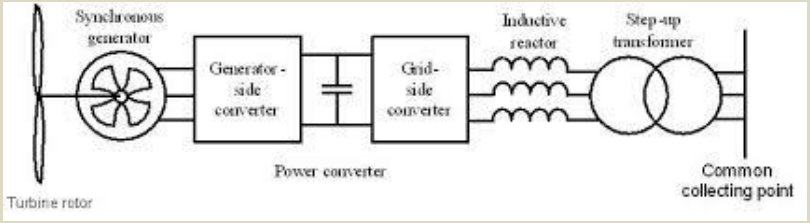
- The characteristics of wind generators are much different from traditional synchronous machine based generation.
- Nature of AC or HVDC transmission used to connect wind to the transmission grid (long ac cables, filters, weak grids, series compensation)



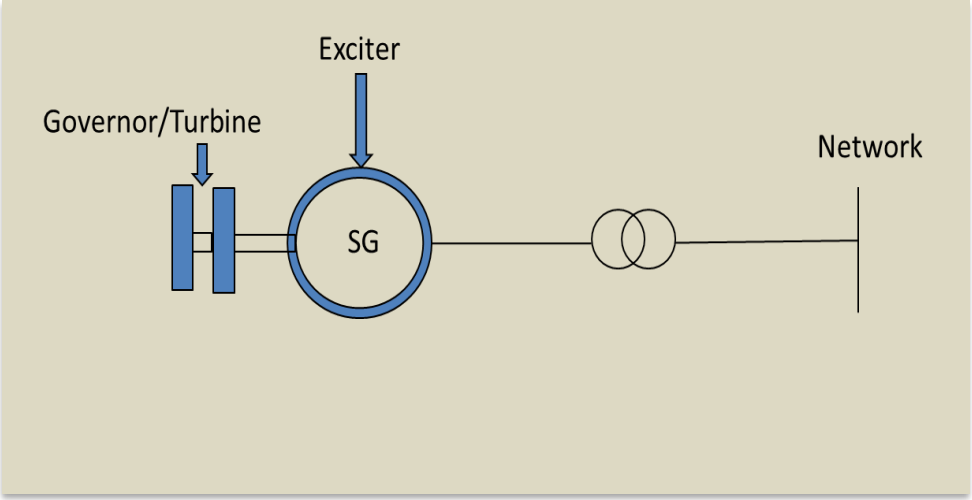
Synchronous Generator Based

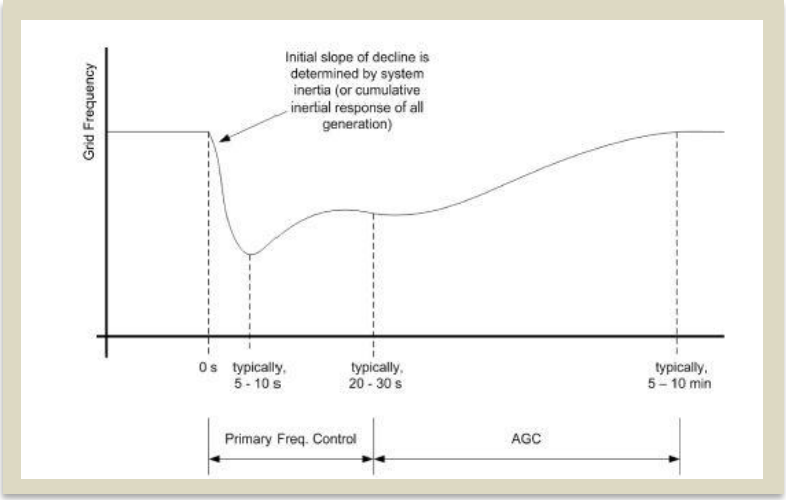


Wind Type 3
Wind Type 4



Characteristics of Synchronous Generators





The Synchronous generator response is determined by

- Machine electrical characteristics
- Exciter characteristics
- Governor / turbine
- Inertia of the rotating masses

The inertial response immediately follows the event

- The inertial response is due to the inertia of large synchronous generators
- Primary control - 20 - 30 Sec
- Power electronic based generation does not provide the same style of ‘inertia’

Wind and Solar PV generation – Based on Power Electronic converter interface – Impact of Network Characteristics

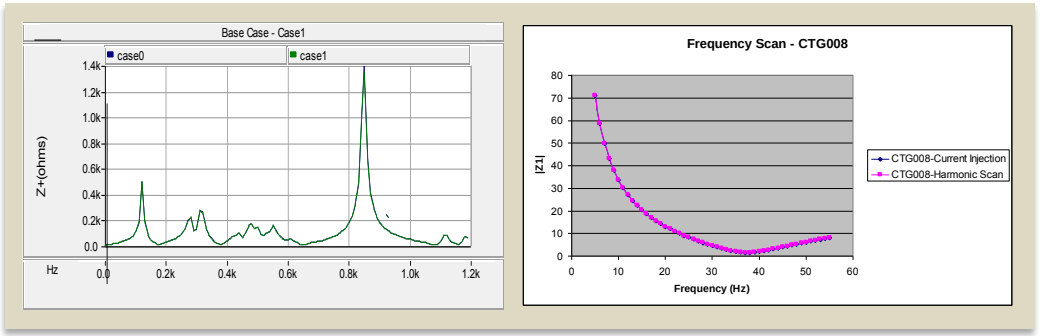
Weak grid (Low short circuit current, high system impedance)

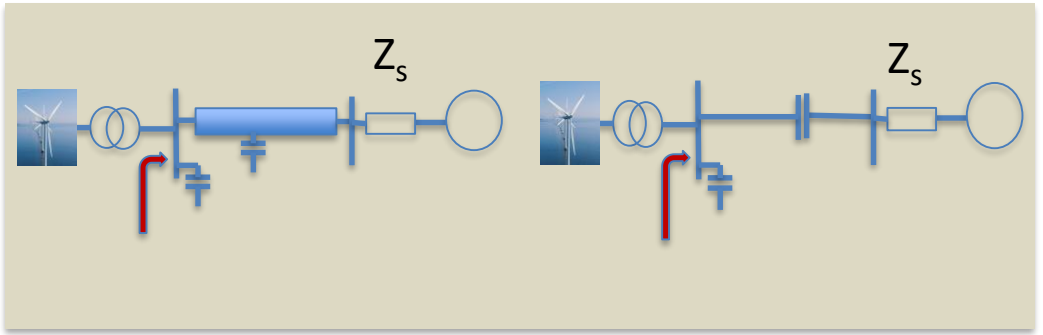
- T3 and T4 controls depend on system voltage and current measurements as inputs
- Weak grids : Changes in system quantities are harder to track following a system event.
  - Specially the change in voltage phase.

Series compensated systems

- Network resonance points in the sub synchronous frequency range (< 50 Hz)

System Impedance Vs Frequency Plots

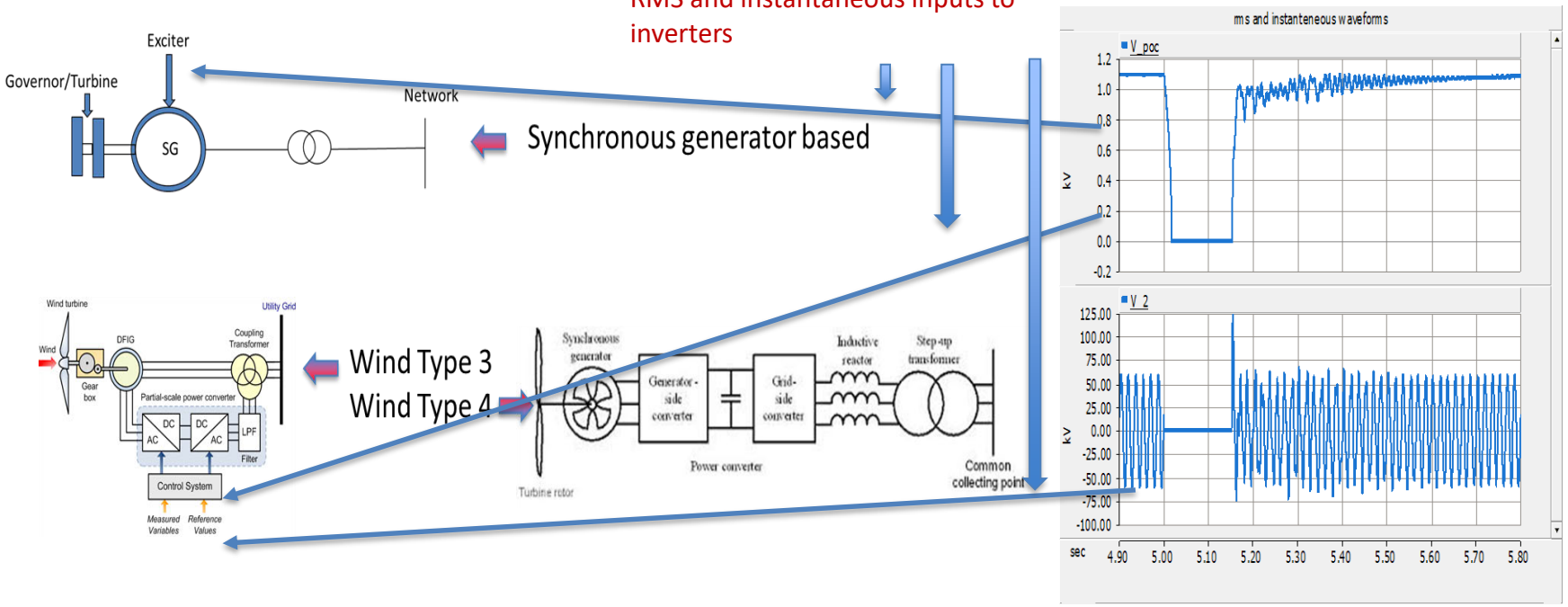




Wind Generators and Transmission characteristics

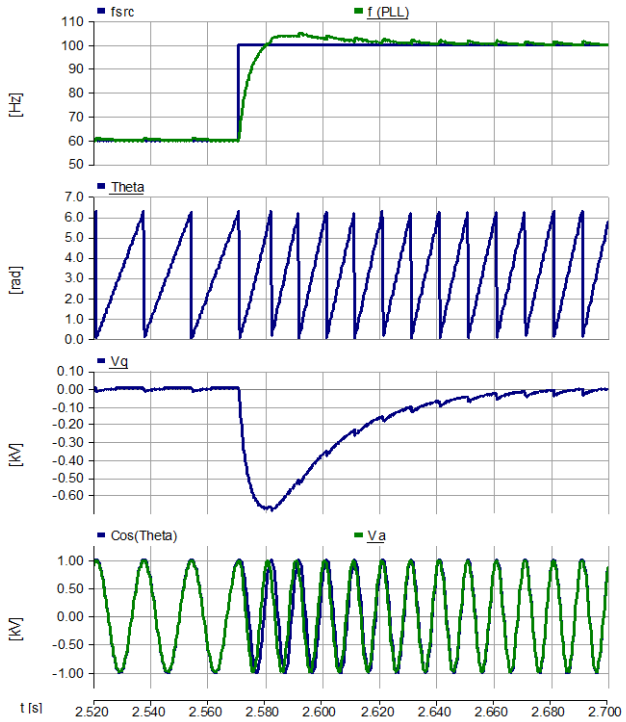
- The dynamic characteristics of wind and Solar PV installations are much different from traditional synchronous machine based generation.
- Nature of AC (or HVDC transmission) used to connect wind to the transmission grid (weak grids, series compensation, long ac cables, filters) has a significant impact on wind/solar PV response following system events.

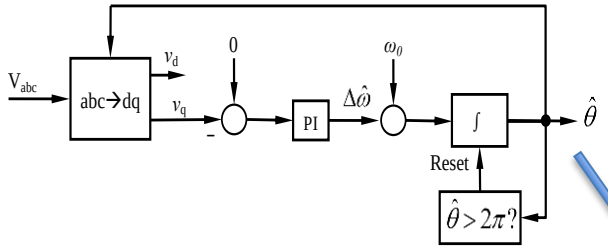
Inputs to generator controls:
RMS and instantaneous inputs to inverters



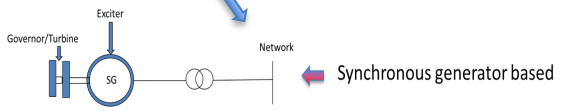
Wind Generators and Transmission Characteristics

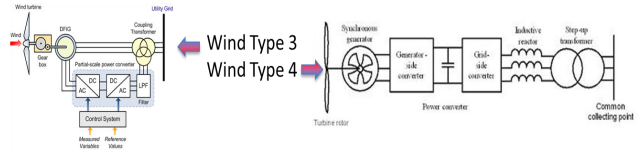
Phase Locked Loop (PLL)





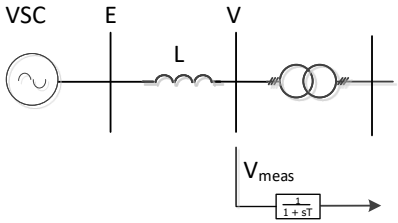
PLL Output to Inverter



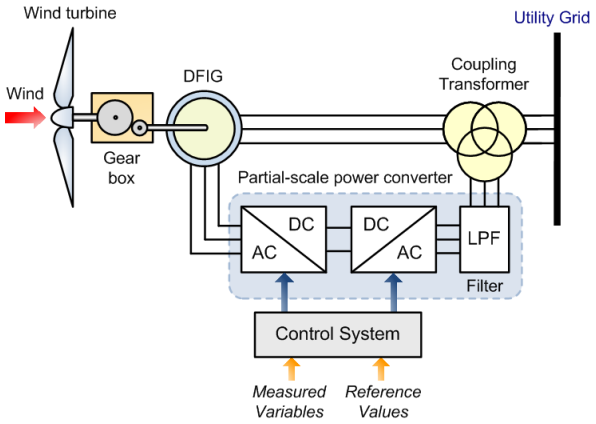


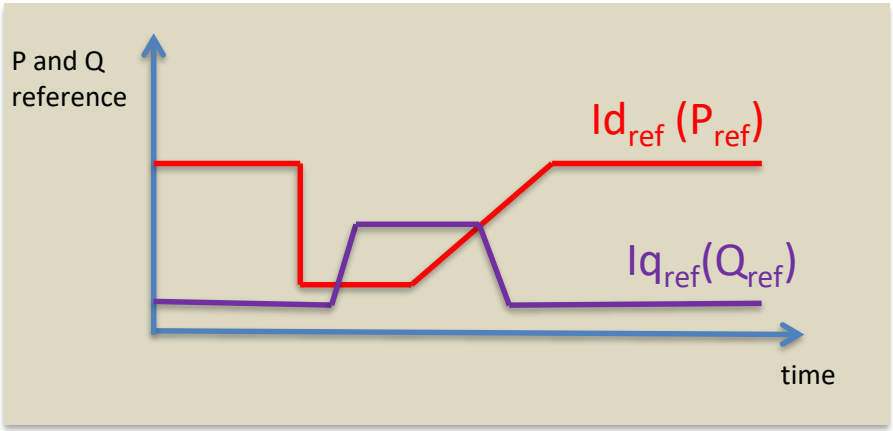
Input to PLL

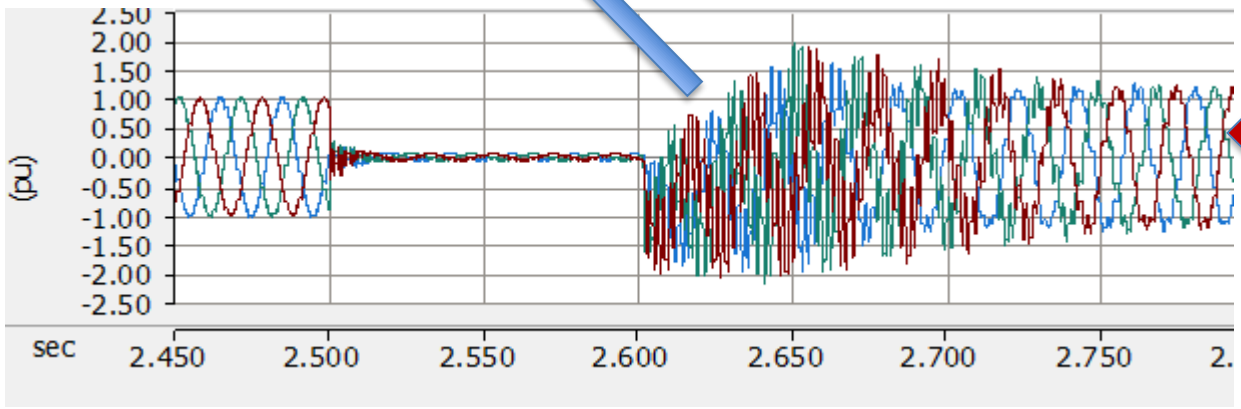
Measurements and signal filtering



Integration of Wind Power to Weak Grids – Example





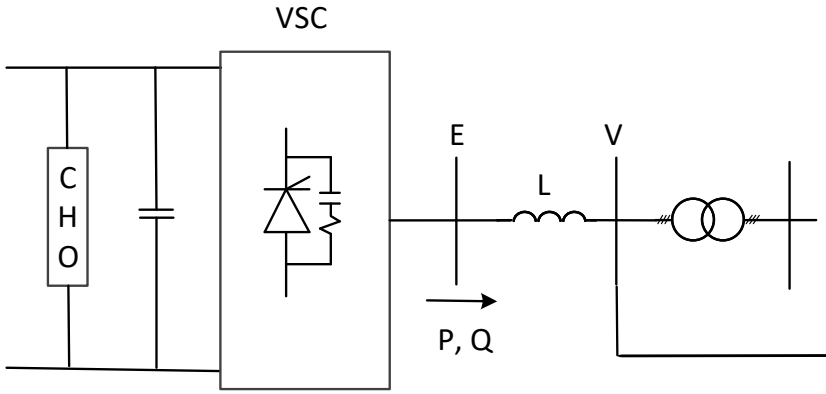


Bus voltage following a fault

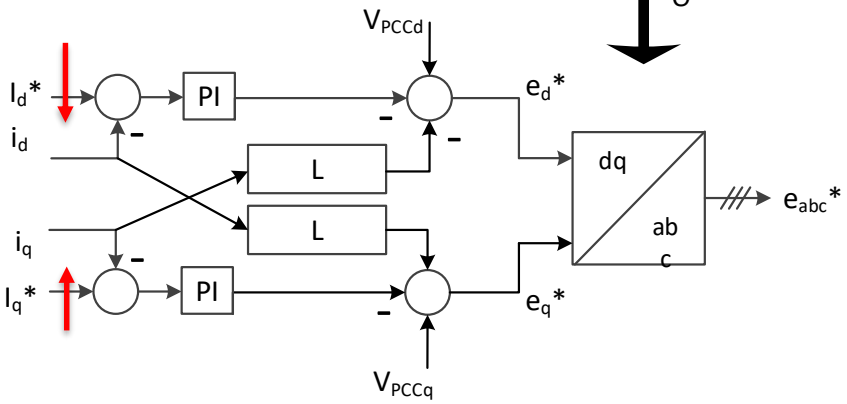
This voltage must be tracked and phase angle shifts estimated accurately and fast to ensure stable operation

Integration of Wind Power to Weak Grids – Example

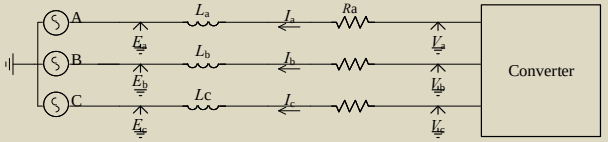
VSC Control Strategies



- EMT simulations must be used to accurately represent the response of the PLL and fast controls.
- This is more of a concern in 'weak grid interconnections' and when there is significant penetration of renewables in an area.



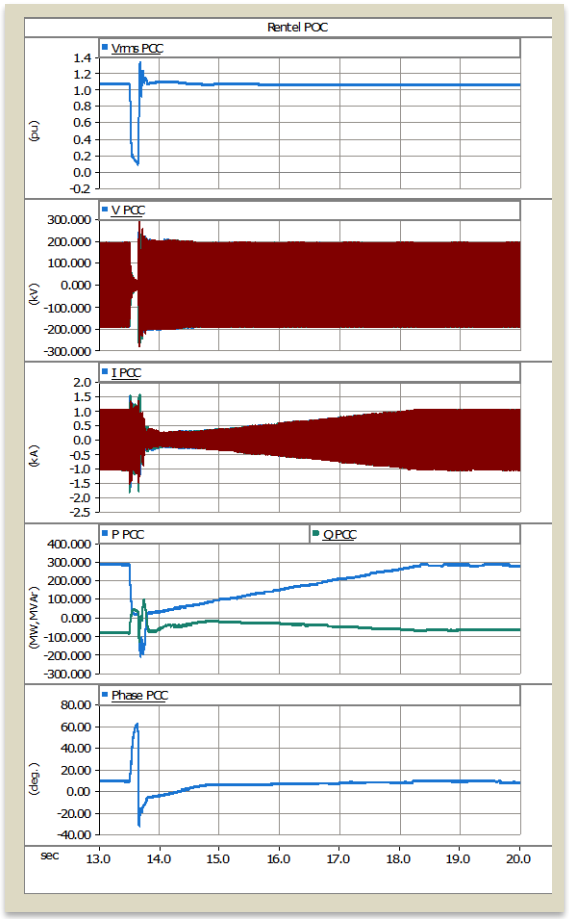
$$\begin{pmatrix} \frac{dI_a}{dt} \\ \frac{dI_b}{dt} \\ \frac{dI_c}{dt} \end{pmatrix} = \begin{pmatrix} \frac{-R}{L} & 0 & 0 \\ 0 & \frac{-R}{L} & 0 \\ 0 & 0 & \frac{-R}{L} \end{pmatrix} \begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} + \frac{1}{L} \begin{pmatrix} V_a - E_a \\ V_b - E_b \\ V_c - E_c \end{pmatrix}$$

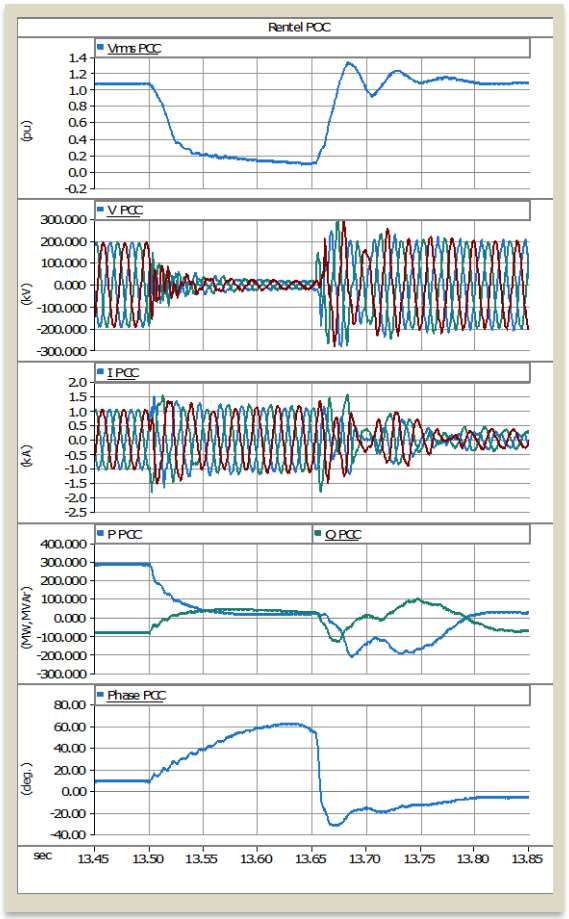


$$\begin{pmatrix} \frac{dI_d}{dt} \\ \frac{dI_q}{dt} \end{pmatrix} = \begin{pmatrix} -\frac{R}{L} & \omega \\ -\omega & -\frac{R}{L} \end{pmatrix} \begin{pmatrix} I_d \\ I_q \end{pmatrix} + \frac{1}{L} \begin{pmatrix} V_d - E_d \\ V_q - E_q \end{pmatrix}$$

Importance of Accurate PLL Response

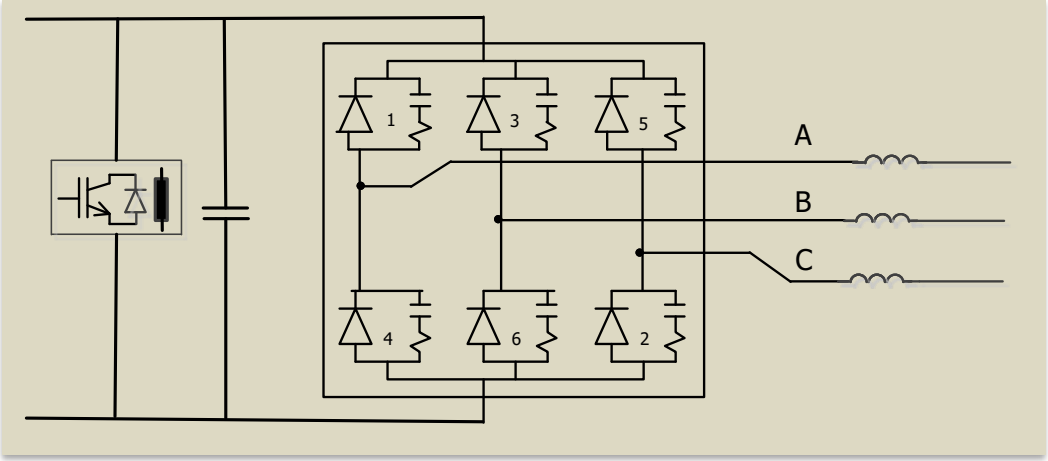
Power reversal as an example - Fault Recovery of an offshore windfarm





Voltage Source Inverters

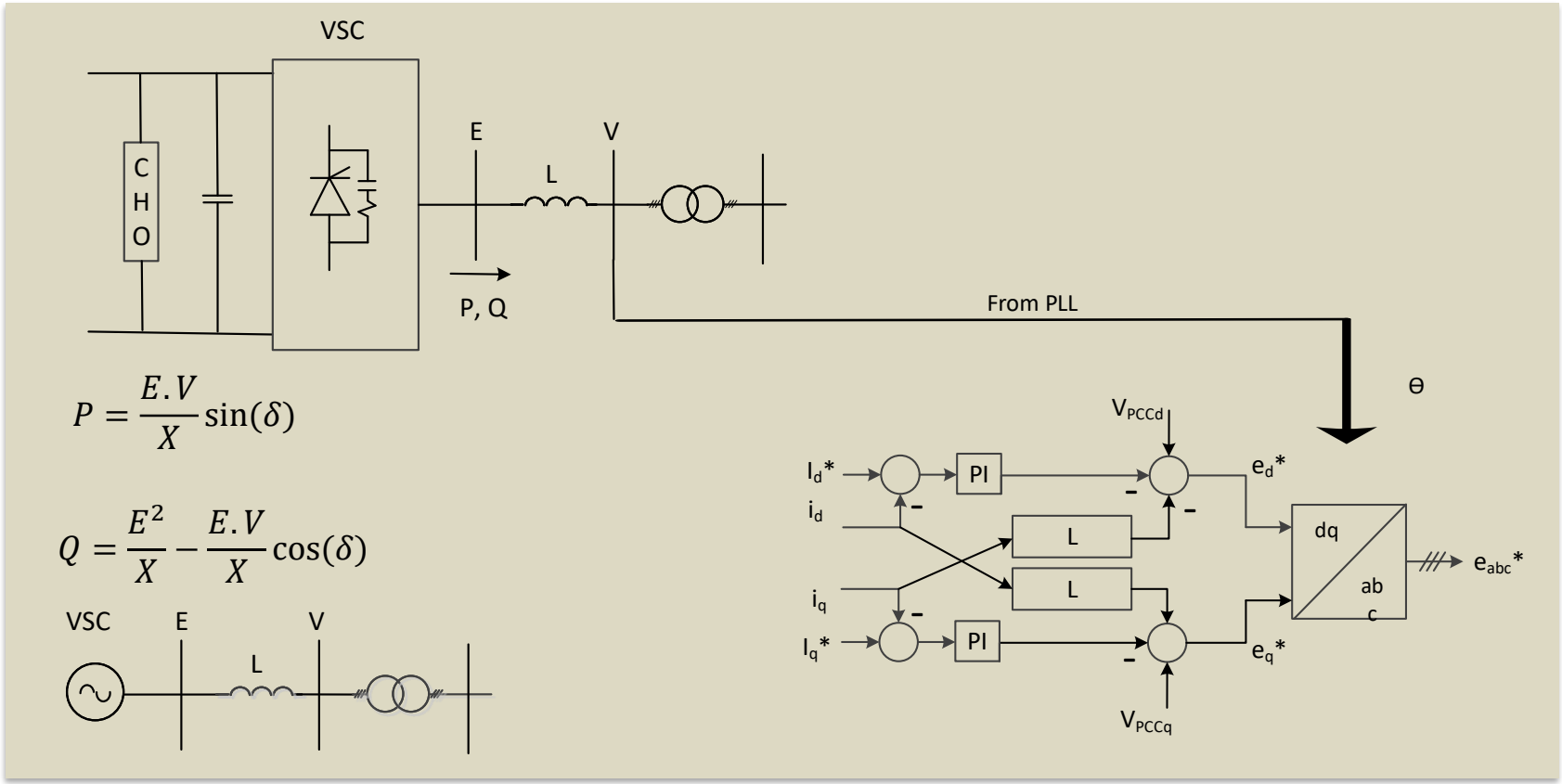
Two Level VSC Topology



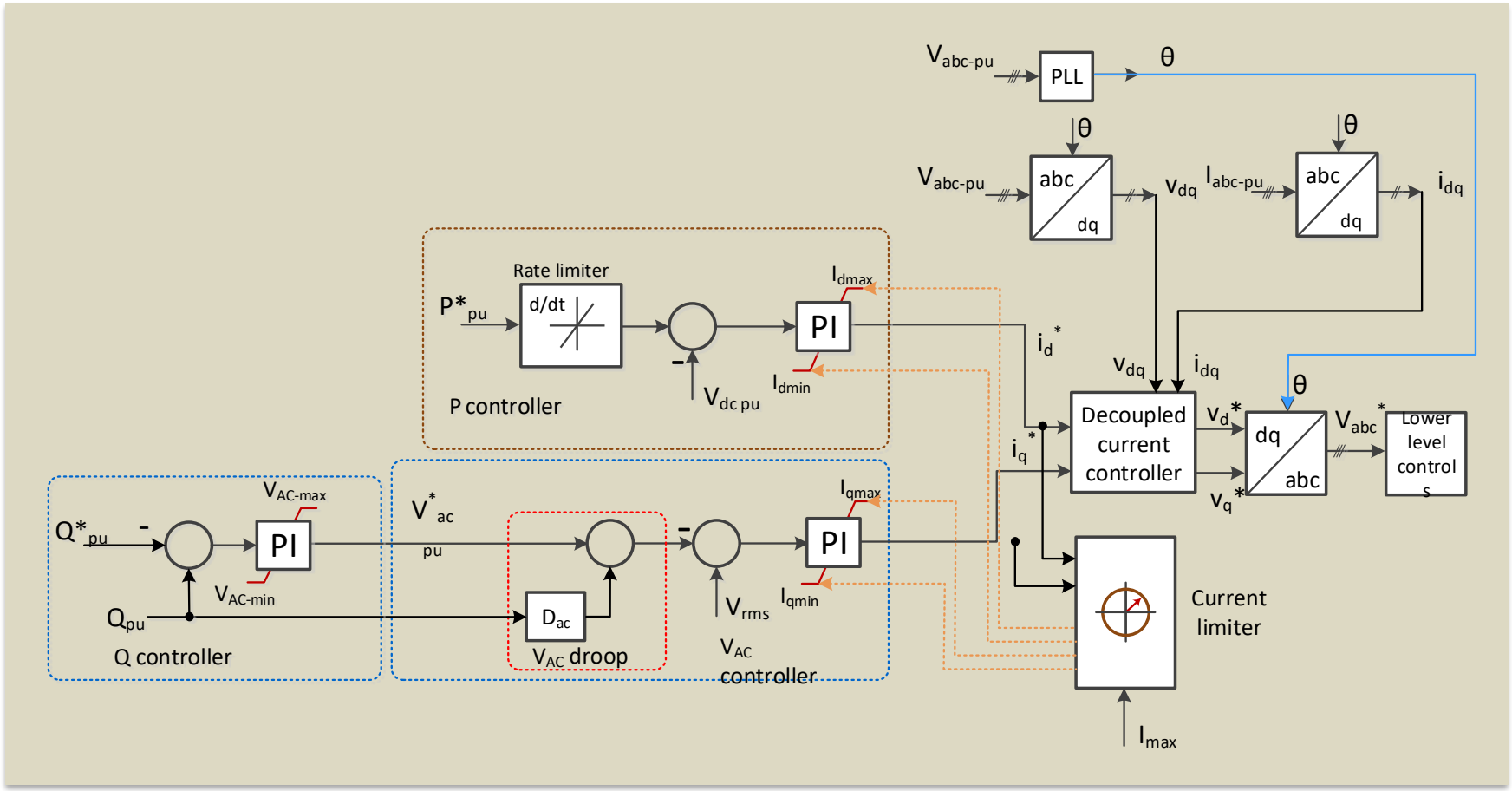
- The firing pulses for the IGBT's are generated by the inverter controls
- DC link voltage should maintained within a narrow band around the rated DC link voltage
- For normal operation ⟹ $V_{dc} > V_{ac,pk}$

Two Level VSC Topology – Control of P and Q

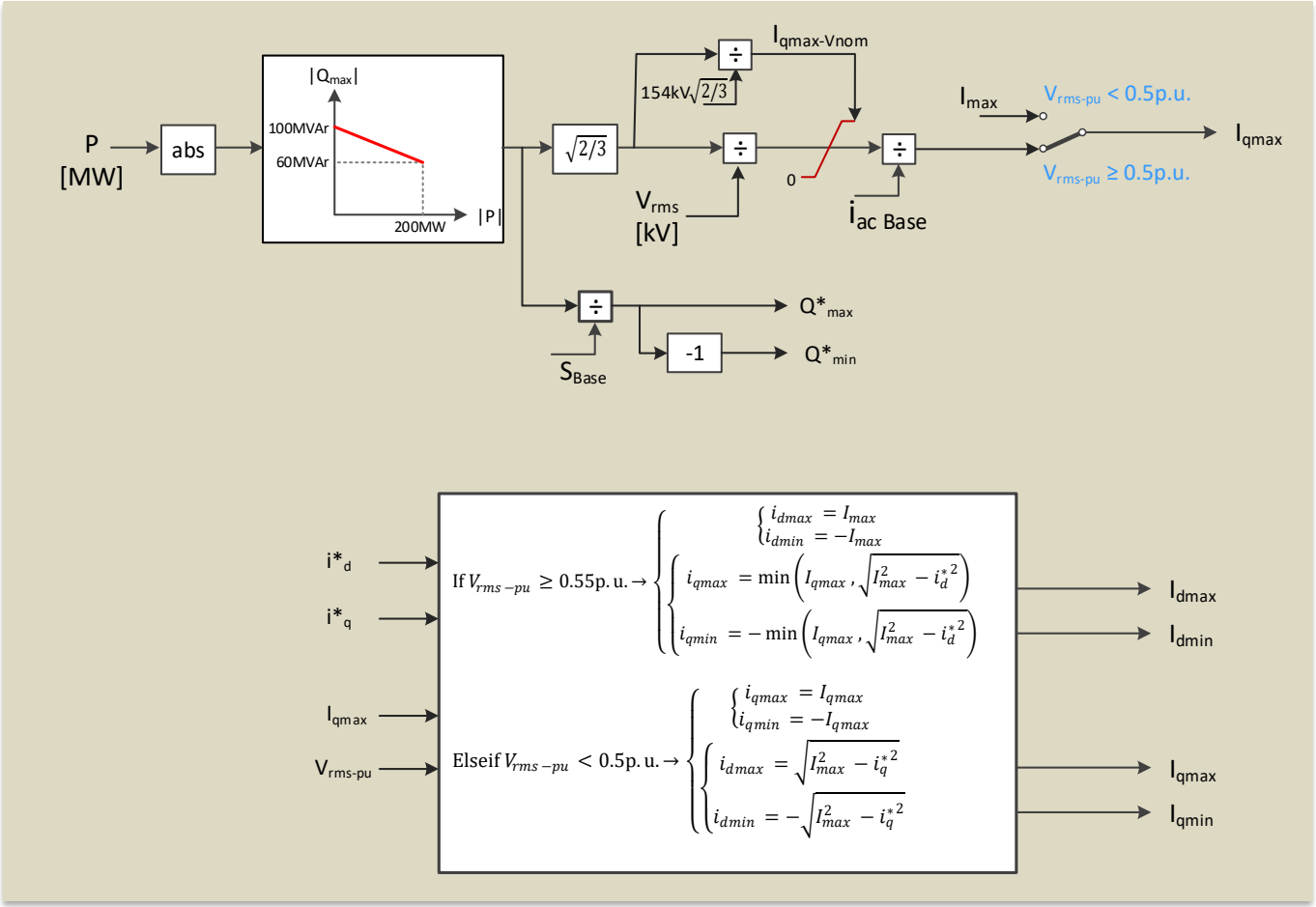
VSC = Voltage Source Converter



VSC Control Functions



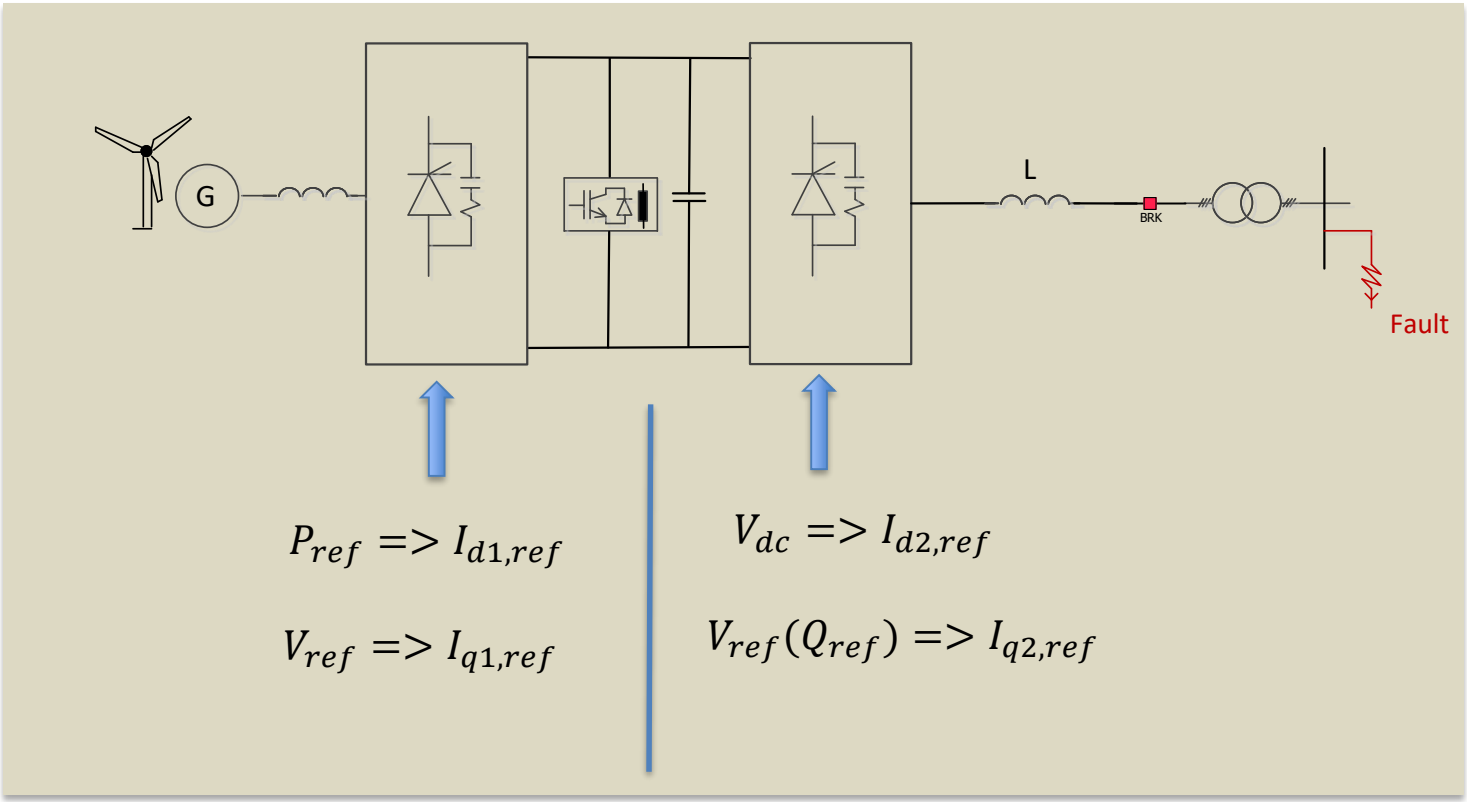
VSC Control Functions - Limits

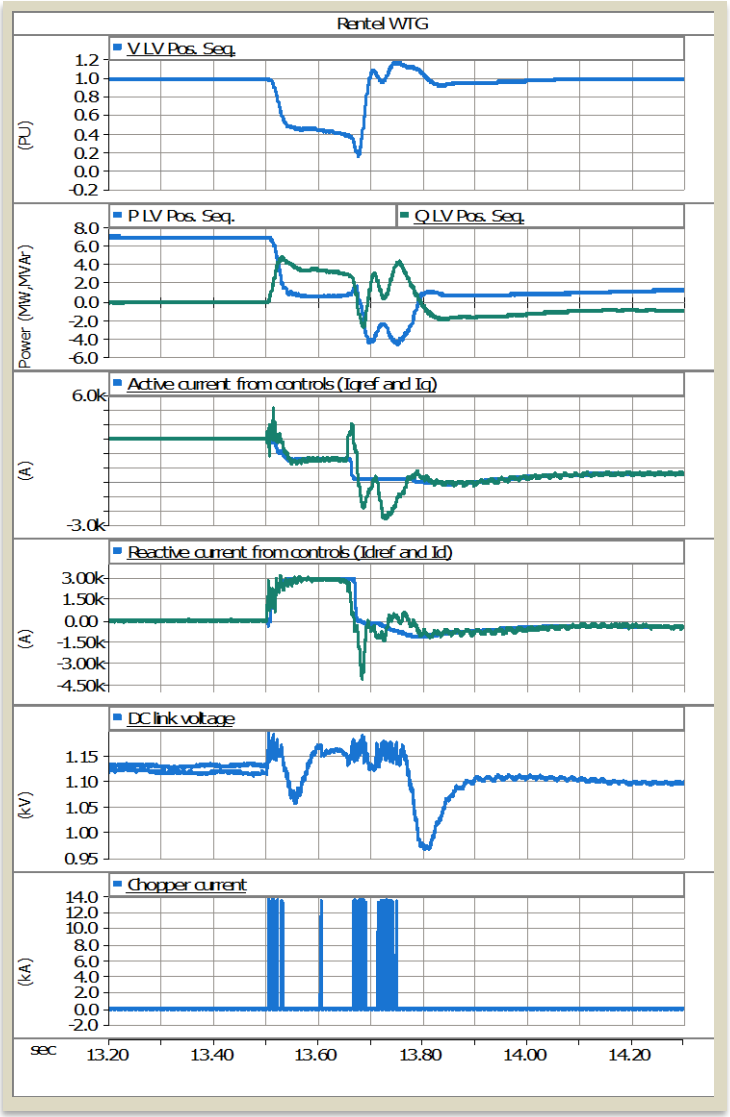


VSC Control Functions – Coordination Between Different Elements

Example:

- Coordination between the two converters and turbine pitch controller
- Action of DC link chopper




Rentel WTG
V LV Pos. Seq.
(PU)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
P LV Pos. Seq.
Q LV Pos. Seq.
Power (MW,MVAr)
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
Active current from controls (Igref and Iq)
(A)
6.0k
-3.0k
Reactive current from controls (Idref and Id)
(A)
3.00k
1.50k
0.00
-1.50k
-3.00k
-4.50k
DC link voltage
(kV)
1.15
1.10
1.05
1.00
0.95
Chopper current
(kA)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
sec
13.20
13.40
13.60
13.80
14.00
14.20

Electromagnetic Transient Simulations

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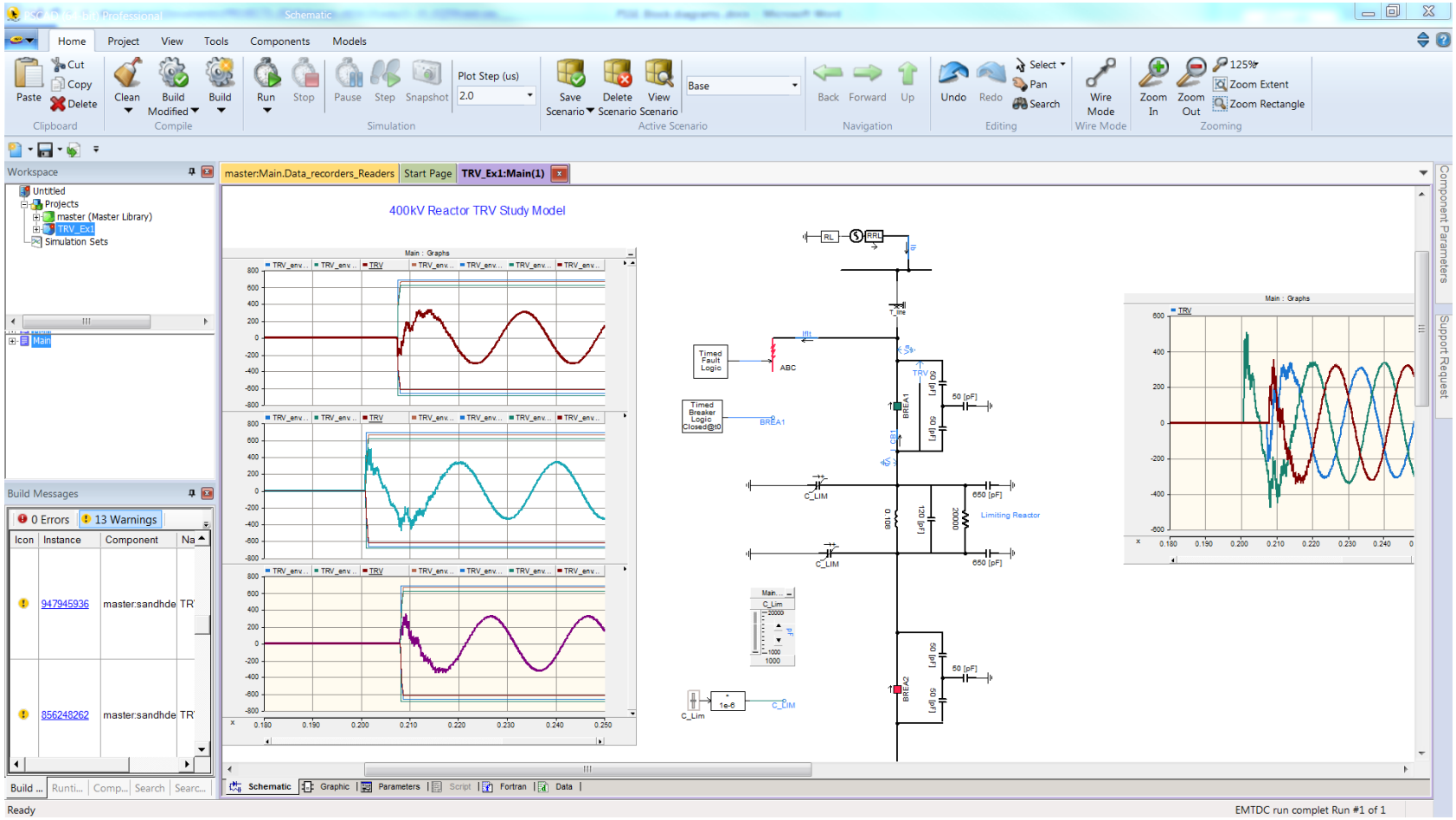
PSCAD/EMTDC – The Industry Standard EMT Program



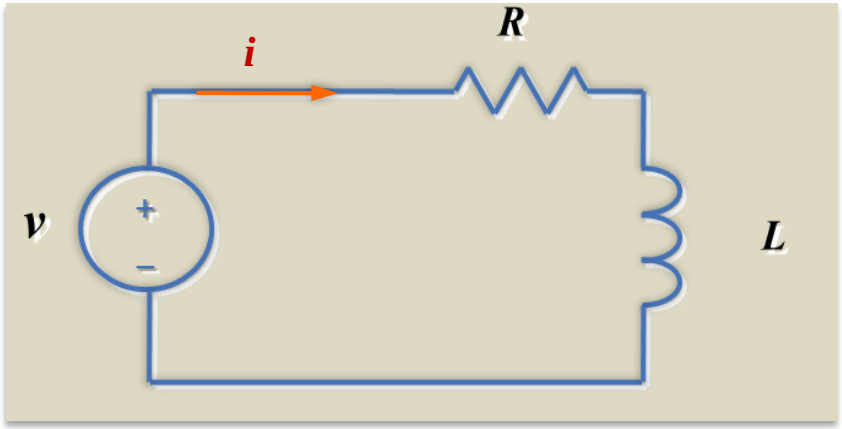
Transients and Steady State

RMS Type Simulations

- Each solution based on phasor calculations
- 50Hz/60 Hz representation of electric network
- Network dynamics are not considered

$$V = (\omega) = R \cdot I\ (\omega) + j(L\omega) \cdot I\ (\omega)$$

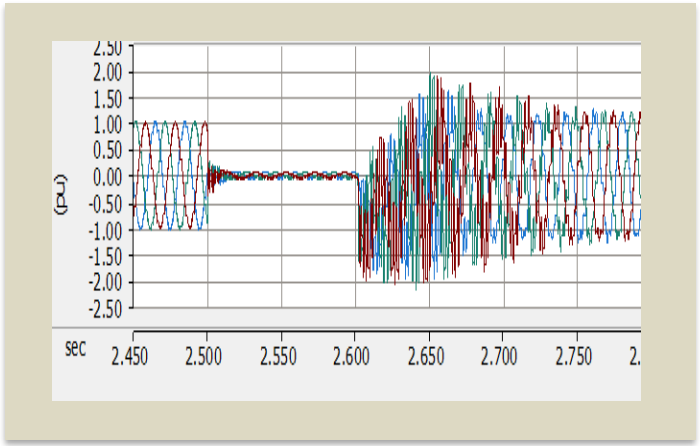
$$\omega = 2.\pi.50$$



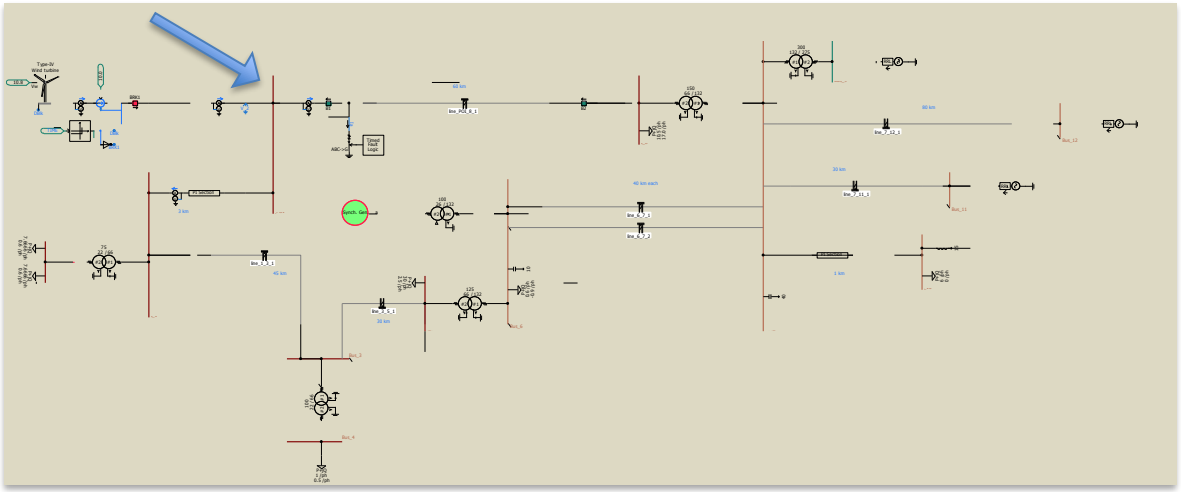
Electro-Magnetic Transient Simulations (EMT)

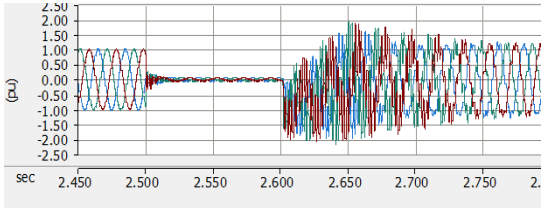
- Direct time domain solution of Differential Equations

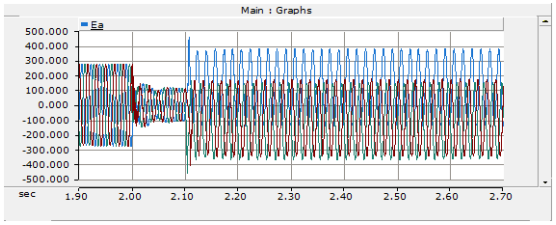
$$v(t) = R \cdot i(t) + L\frac{d}{dt}\ i\ (t)$$



EMT Vs RMS Response



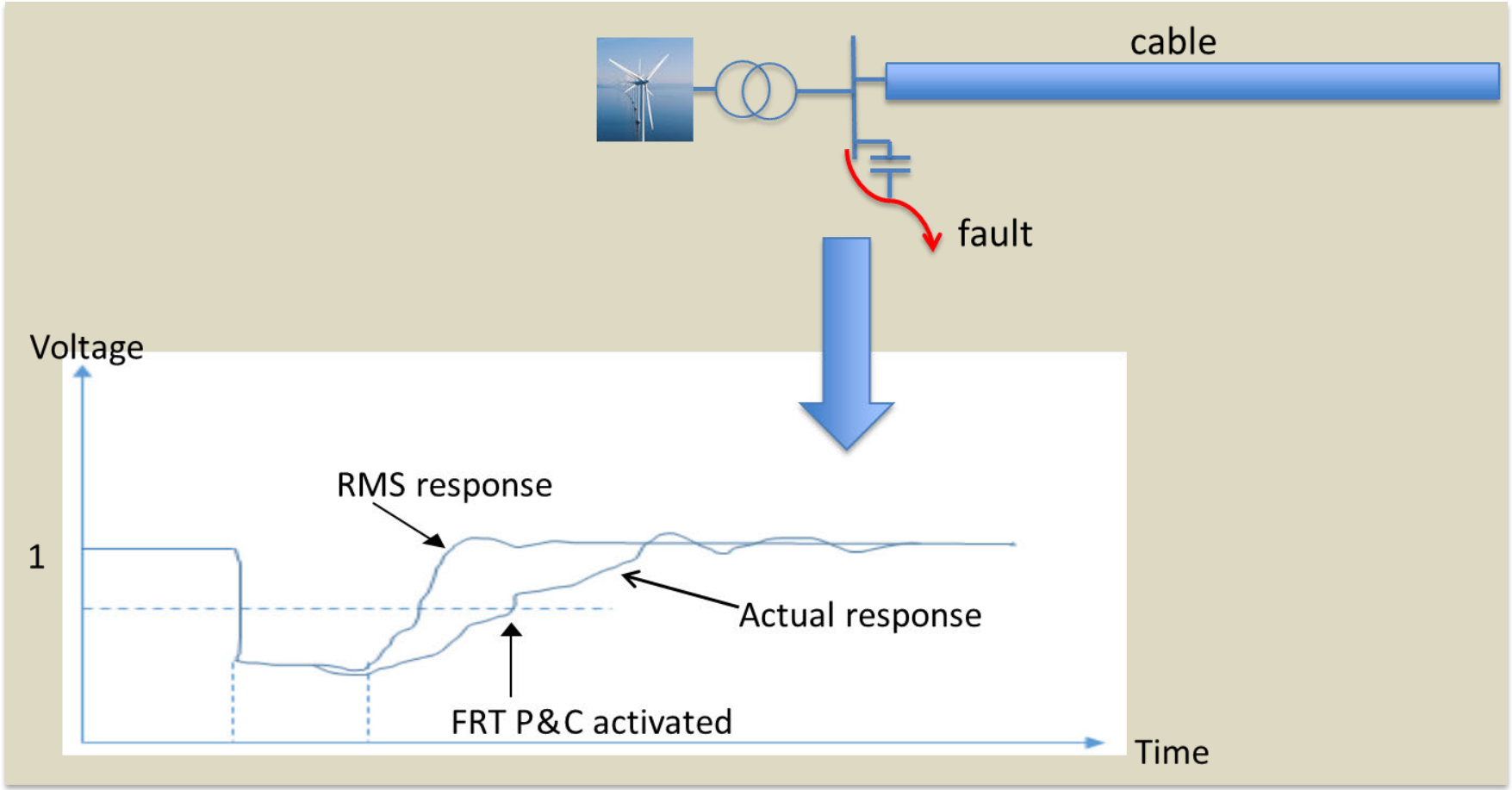




- Harmonics
- DC offset in currents and voltages are represented
- Fast controls of inverters can be better represented
- Interaction between fast acting power electronic devices can be studied
- Accurate representation of PLL
- However, EMT simulations are slow compared to RMS type simulations

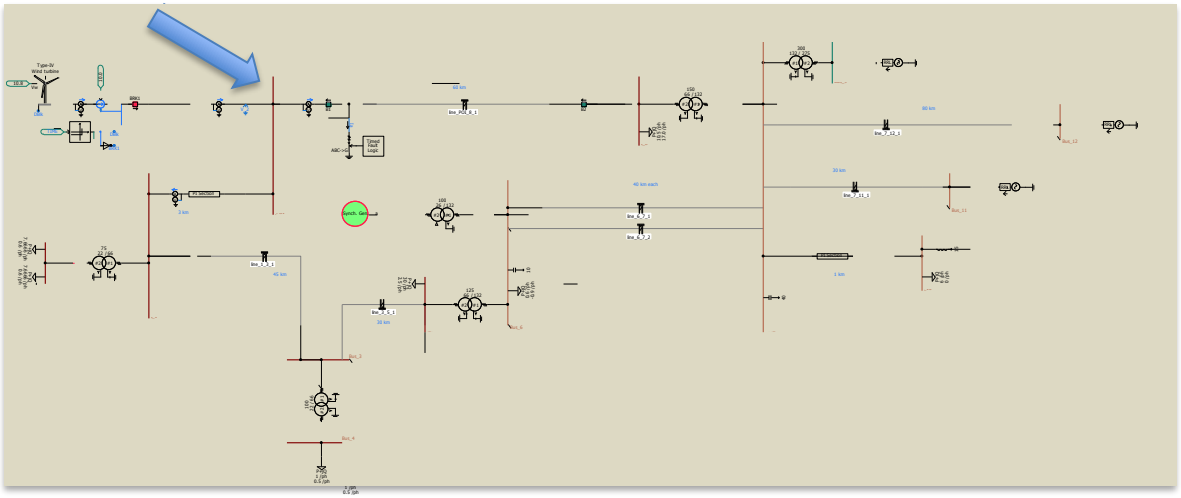
EMT Vs RMS Response - Example

Fault Ride Through response of a wind farm



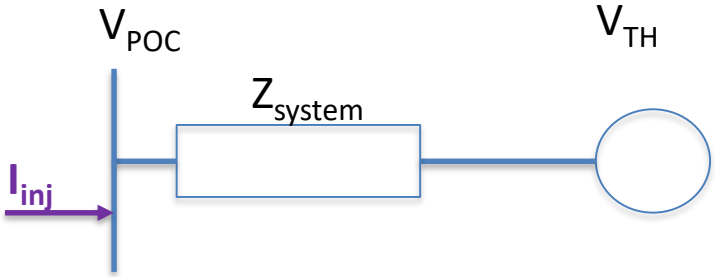
Weak Grids

Weak Grids – Low Short Circuit Ratio (SCR)



A ‘weak’ Point of connection (POC) (‘weak’ grid)

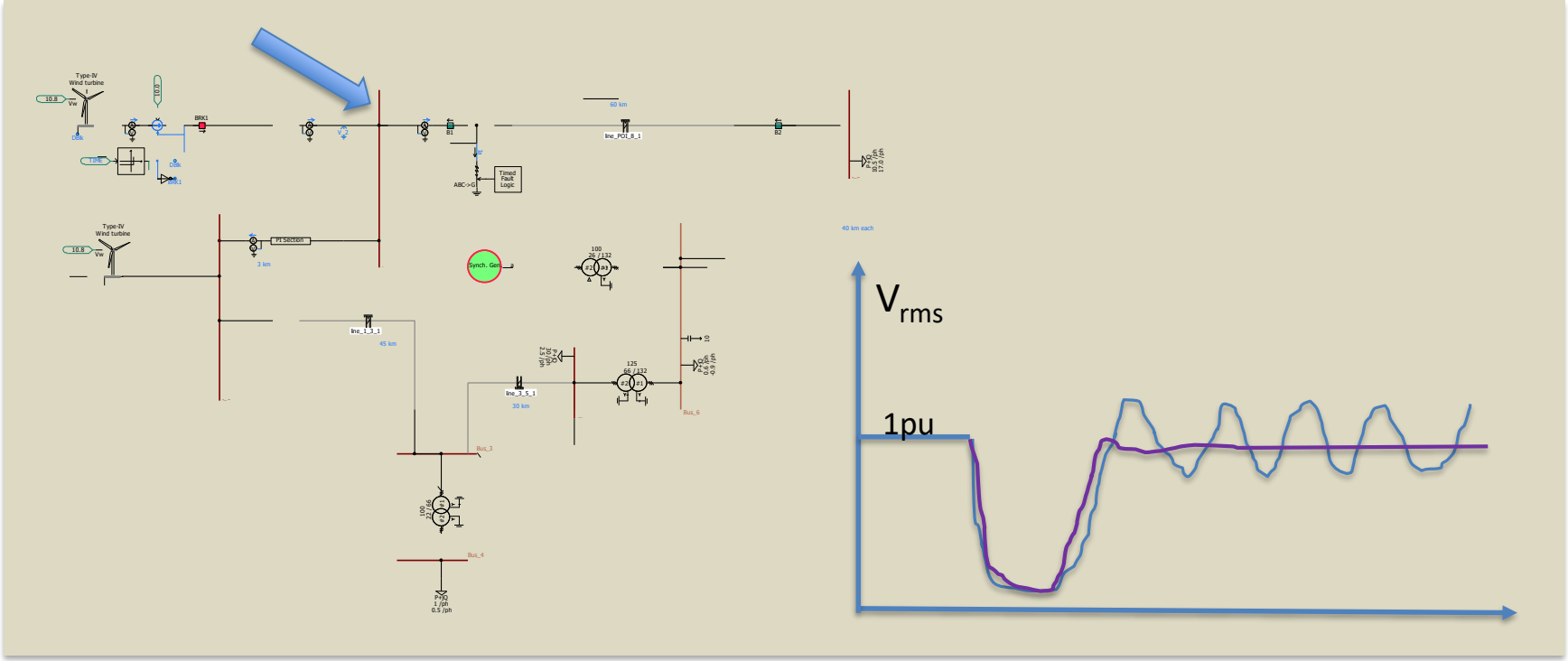
- Low short-circuit current level at POC
- High system impedance



Injection of P and Q (Current) at a weak POC will lead to voltage variations at the bus

$$V_{POC} = I_{inj} \times Z_{system} + V_{TH}$$

Weak Grids – Undesirable Interactions

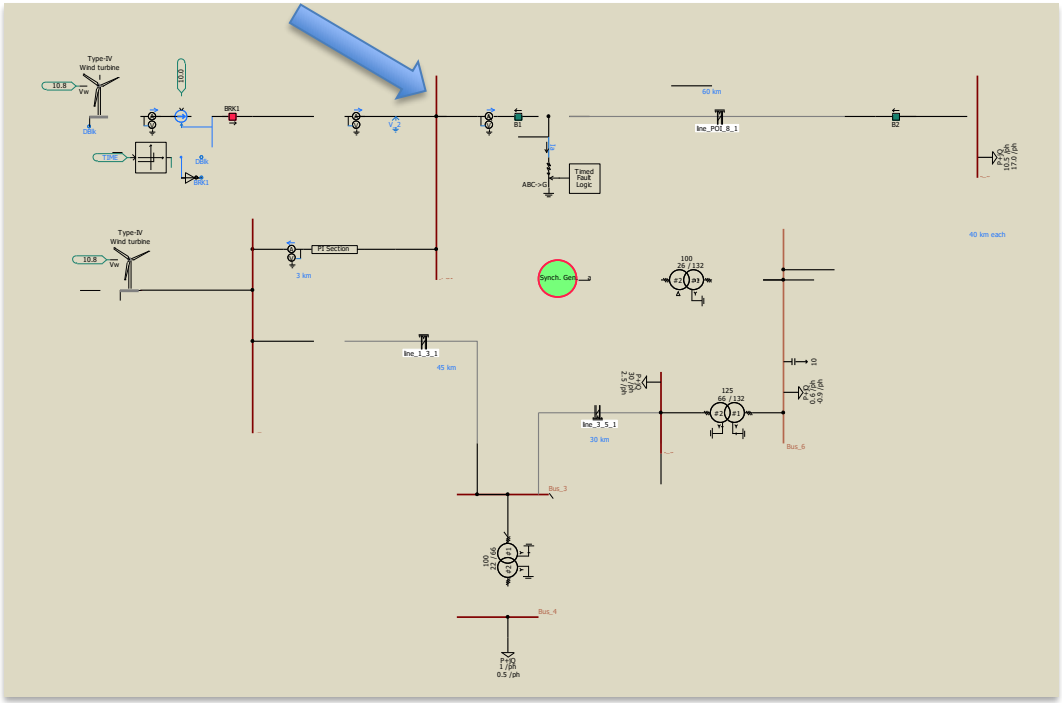


Injection of P and Q (Current) at a weak POC will lead

to voltage variations at the bus

Small Q Injection → ‘Large’ Voltage Change

Weak Grids – Undesirable Interactions

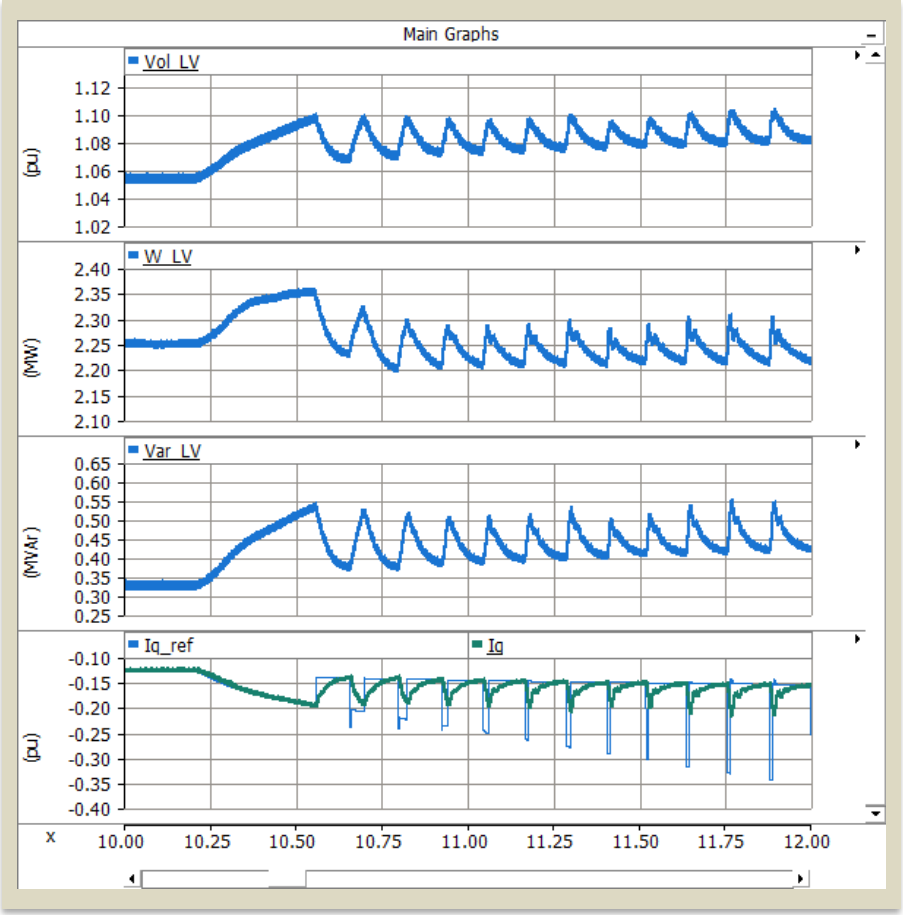


EMT simulations are required to verify acceptable operation.

- *Two or more 'fast' voltage controllers*
- *'Weak' POI ?*
- *Comparable Q controls responses ?*

Weak Grids – Undesirable Interactions

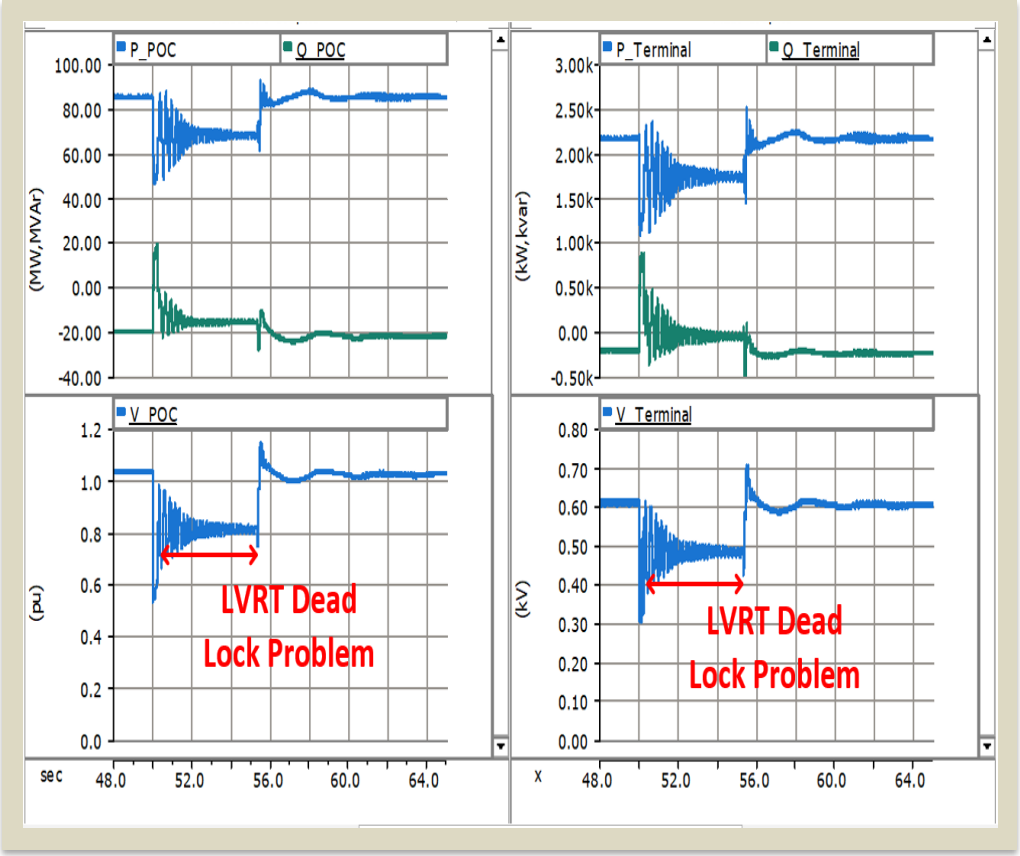
Illustrative example: Control Related Issues - HVRT



Note the I_q reference (from fault Ride Through protection and control of inverter)

Weak Grids – Undesirable Interactions

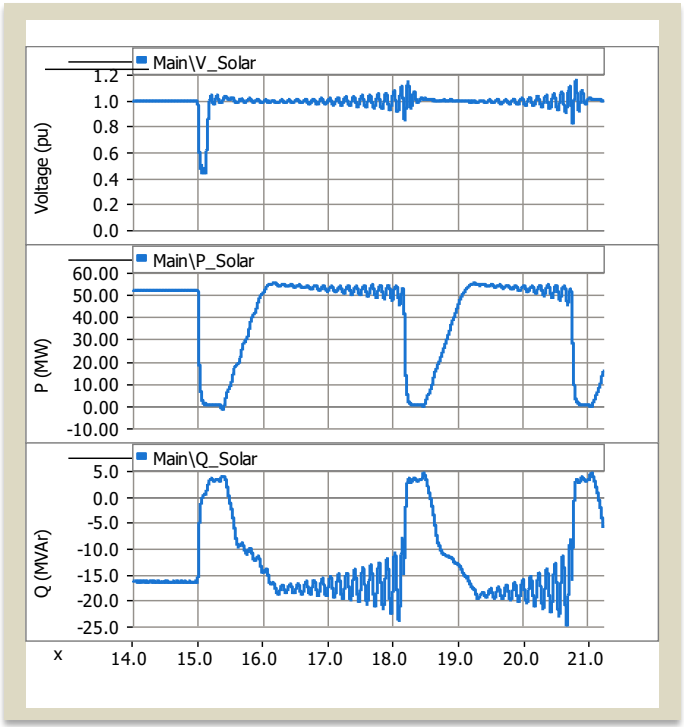
Illustrative example: Control Related Issues - HVRT



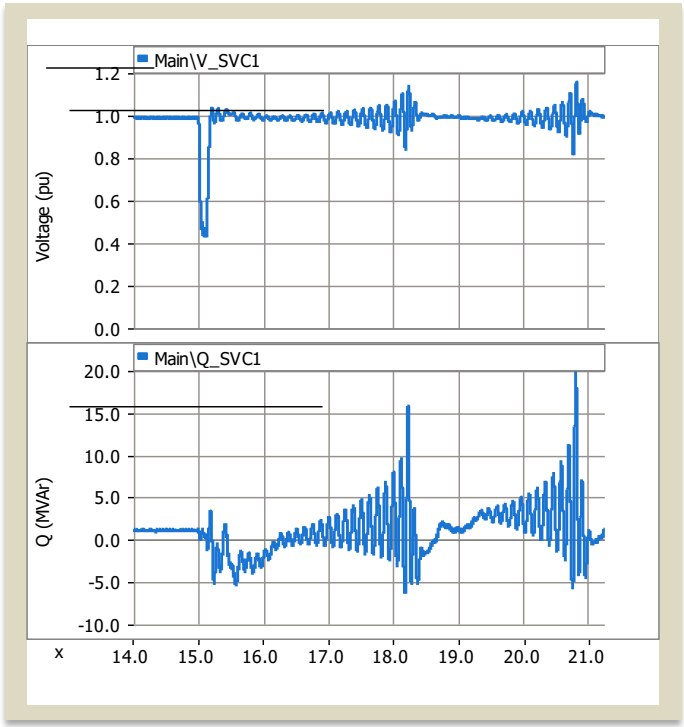
- Voltage drop is relatively low.
- The LVRT reactive current injection is 'proportional' to the magnitude of voltage drop
- Iq injection is insufficient to help voltage recovery
  - Not necessarily a WTG control issue

Weak Grids – Undesirable Interactions

Illustrative example: Interaction between two devices



Solar Farm

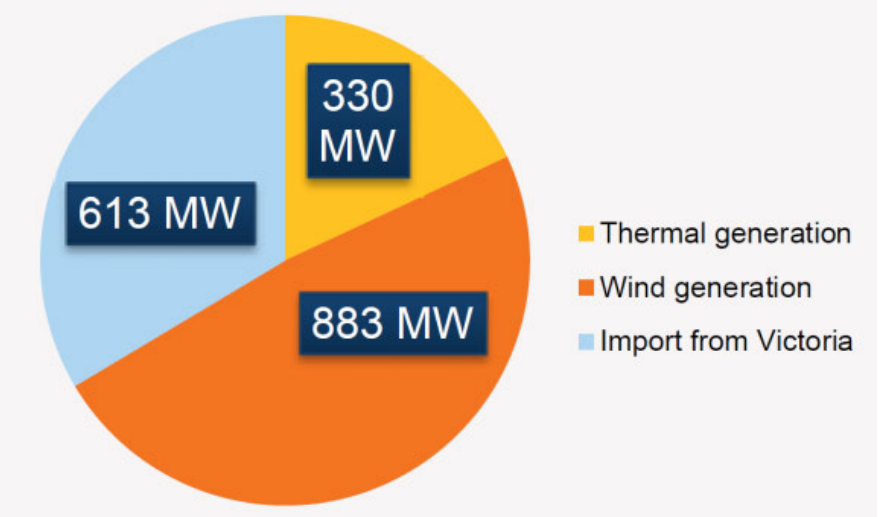


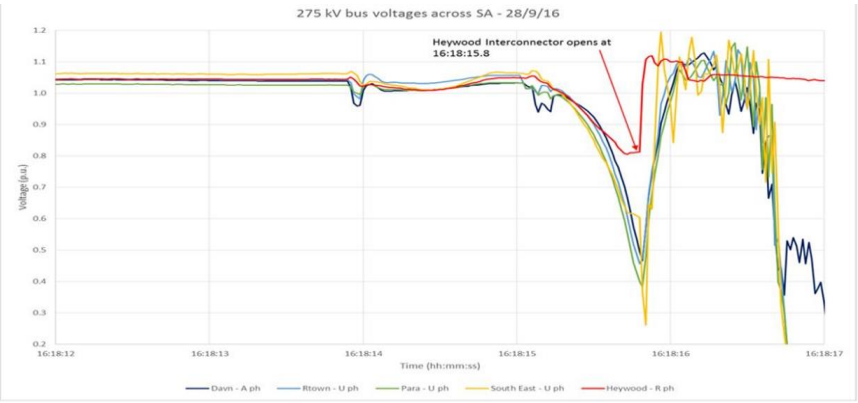
SVC

Practical Examples

Example 1 – Black System South Australia – September 28, 2016

Example 3 – Black System South Australia – September 28, 2016





Black System South Australia – September 28, 2016

Event Description

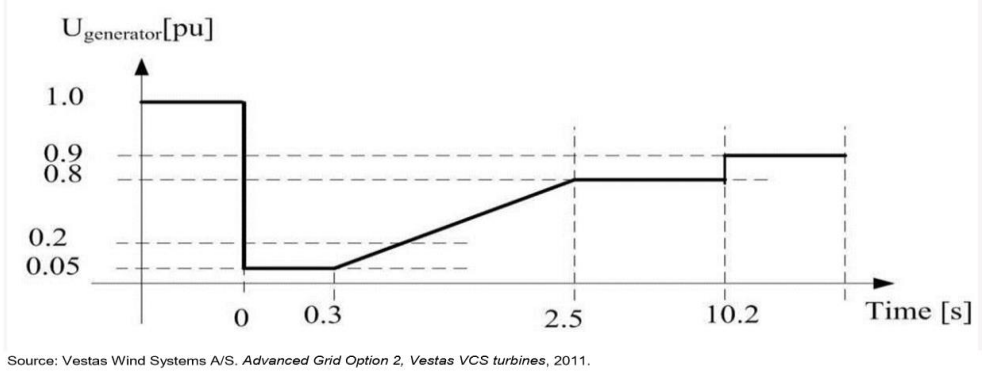
- Extreme weather conditions resulted in five system faults on the SA transmission system in the 87 seconds between 16:16:46 and 16:18:13, with three transmission lines ultimately brought down.
- In response to these faults, and the resulting six voltage disturbances, there was a sustained reduction of 456 MW of wind generation to the north of Adelaide.
- Increased flows on the Heywood Interconnector counteracted this loss of local generation by increasing flows from Victoria to SA.
- This reduction in generation and increase of imports on the Interconnector resulted in the activation of Heywood Interconnector's automatic loss of synchronism protection, leading to the 'tripping' (disconnection) of both of the transmission circuits of the Interconnector. As a result, approximately 900 MW of supply from Victoria over the Interconnector was immediately lost.
- This sudden and large deficit of supply caused the system frequency to collapse more quickly than the SA Under-Frequency Load Shedding (UFLS) scheme was able to act.
- Without any significant load shedding, the large mismatch between the remaining generation and connected load led to the system frequency collapse, and consequent Black System.

Black System South Australia – September 28, 2016

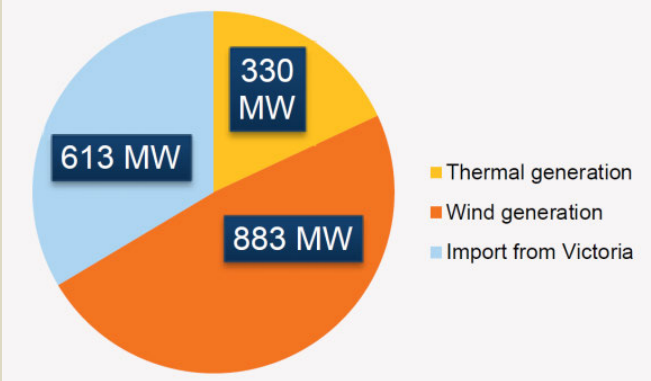
Fault ride through requirement of wind farms

- Wind farms did meet the ride through requirement for the number of faults within the short duration

- However, an additional protection that was not known to system operators got activated to trip some of the wind farms (more than 3-4 faults experienced within a pre defined short duration)



Source: Vestas Wind Systems A/S. *Advanced Grid Option 2, Vestas VCS turbines*, 2011.



Black System South Australia – September 28, 2016

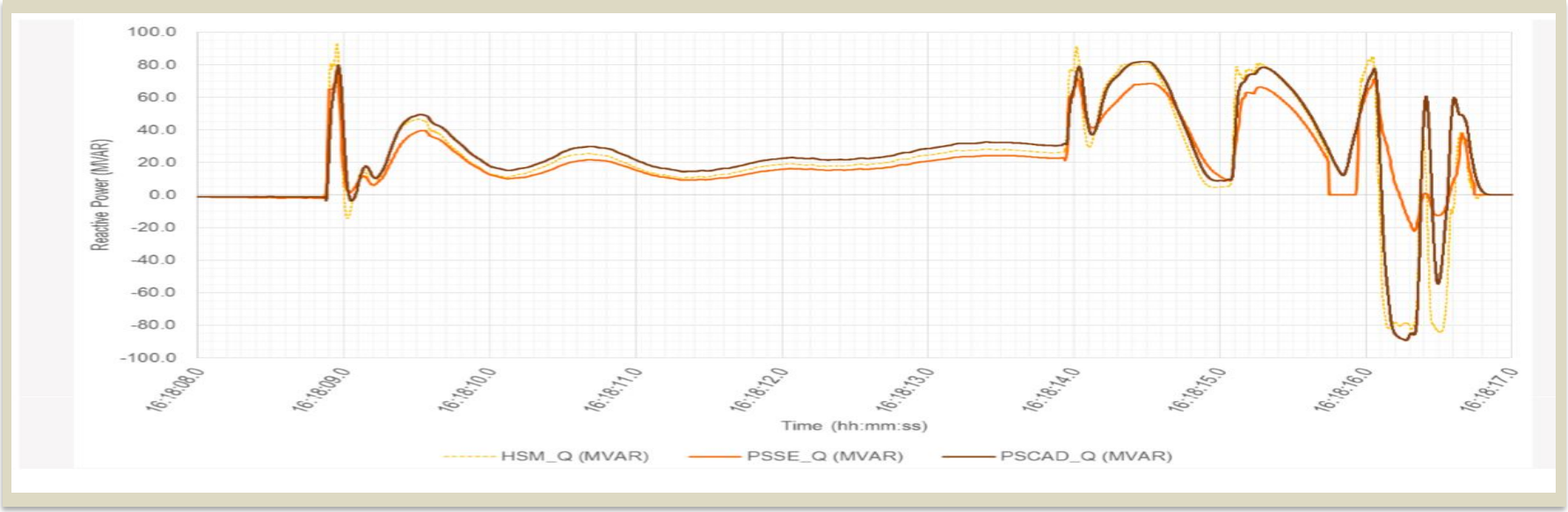
Lessons Learned and Recommendations

Generation Mix and System Inertia:

- The system inertia on the SA side was not sufficient to maintain the frequency drop (once the Haywood interconnector tripped) and to make the under frequency load shedding (UFLS) effective.
- 'Must run' thermal generation may have to be identified.
- Synchronous condensers may be investigated as a potential solution if the thermal generation dispatch is expected to be low under specific load conditions.
- Load shedding

Black System South Australia – September 28, 2016

System Studies – Model Validity



Reference:

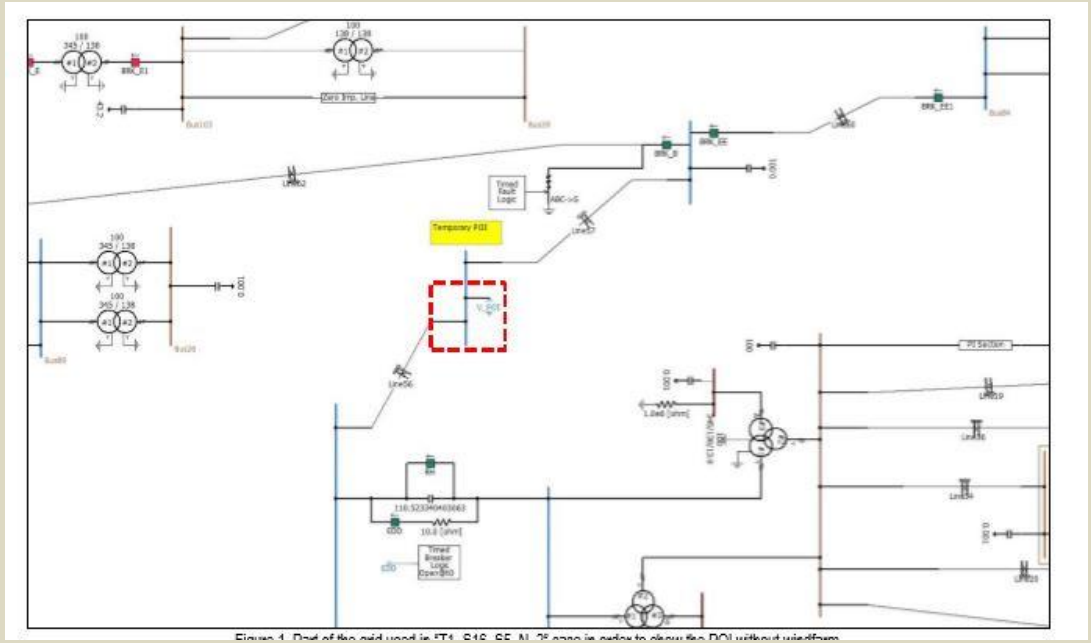
BLACK SYSTEM SOUTH AUSTRALIA 28 SEPTEMBER 2016 - Report by AEMO

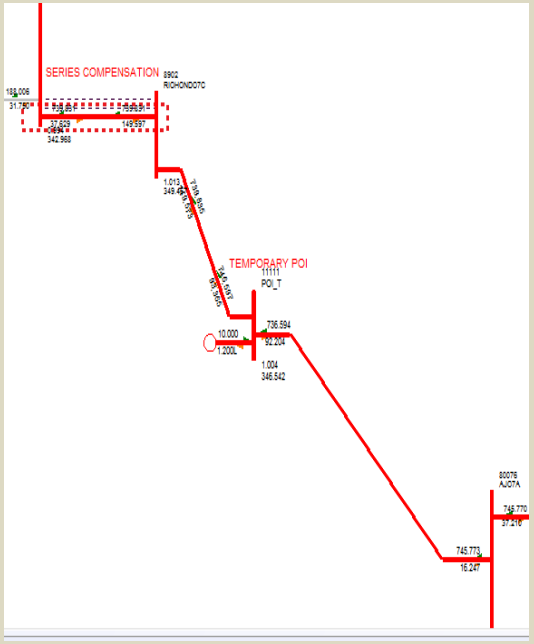
www.aemo.au

Example 2 –300 MW Wind Farm near Series Compensated 345 kV line – SSCI and Interaction with Network Transients

Wind Farms Near Series Compensated Lines

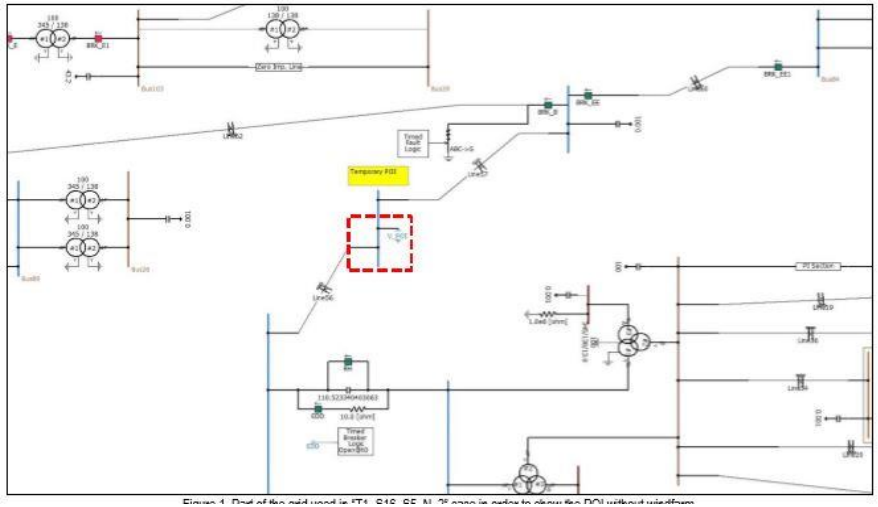
The series compensated line is tapped to facilitate the wind farm connection

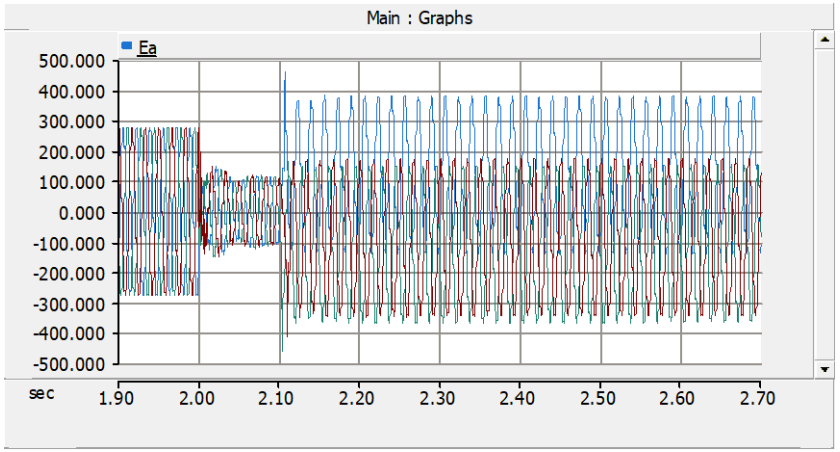


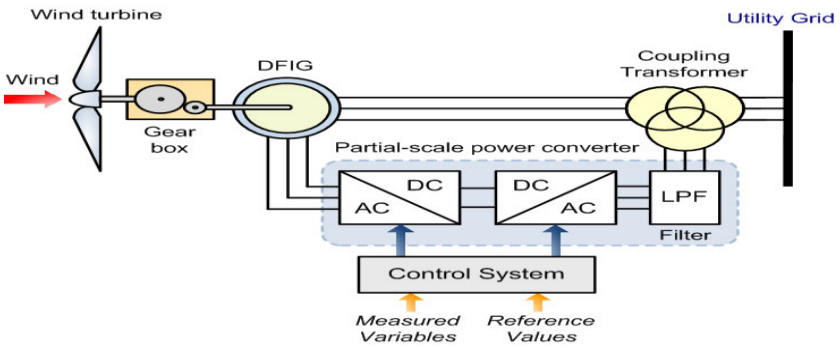


Wind Farms Near Series Compensated Lines

Issue No.2: Wind Inverter response to system transients





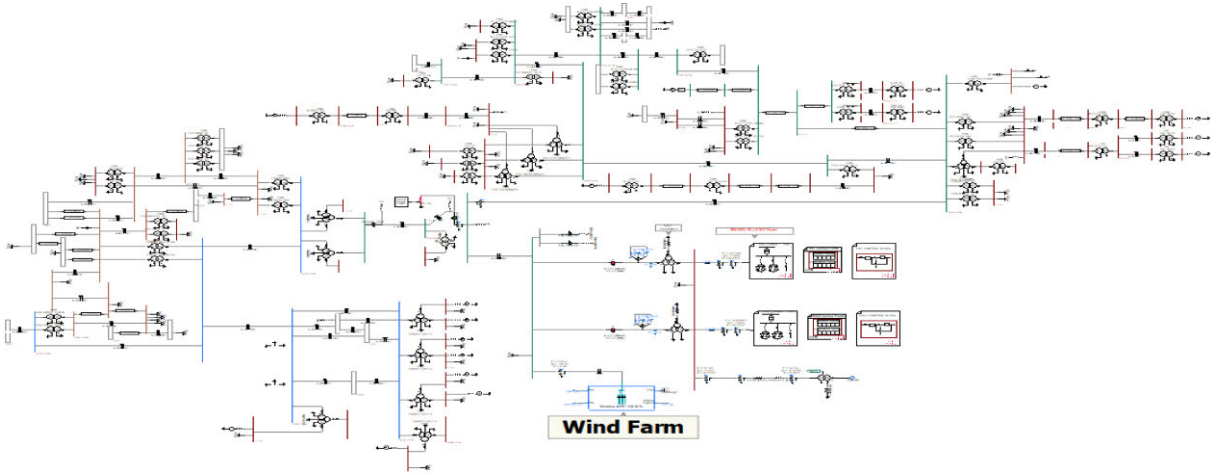


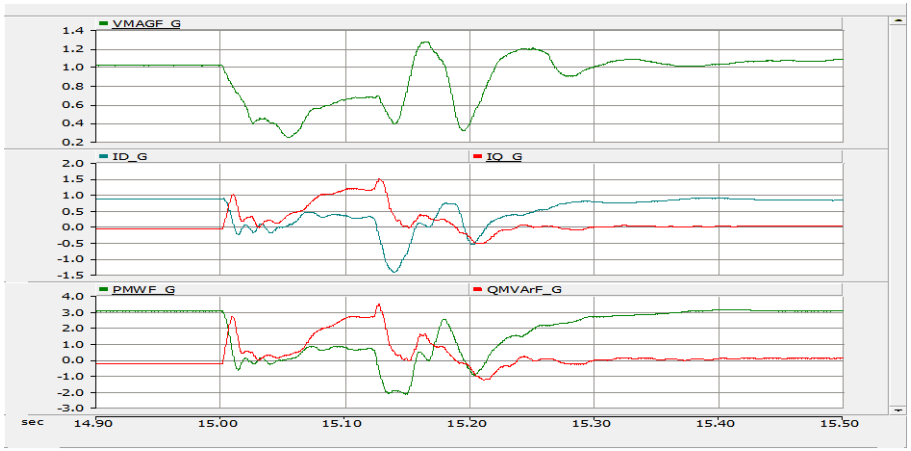
The DC offset in the POI voltage caused the inverter DC link voltage to rise.

- Poor network side damping
- Excessive energy in DC link chopper resistance (resulted in a trip)

Example 3 – Multiple Inverter Based Devices in a Local Area – Control Interactions in a Weak Grid Area

Example 1 - Control Interaction - 200 MW Windfarm Example

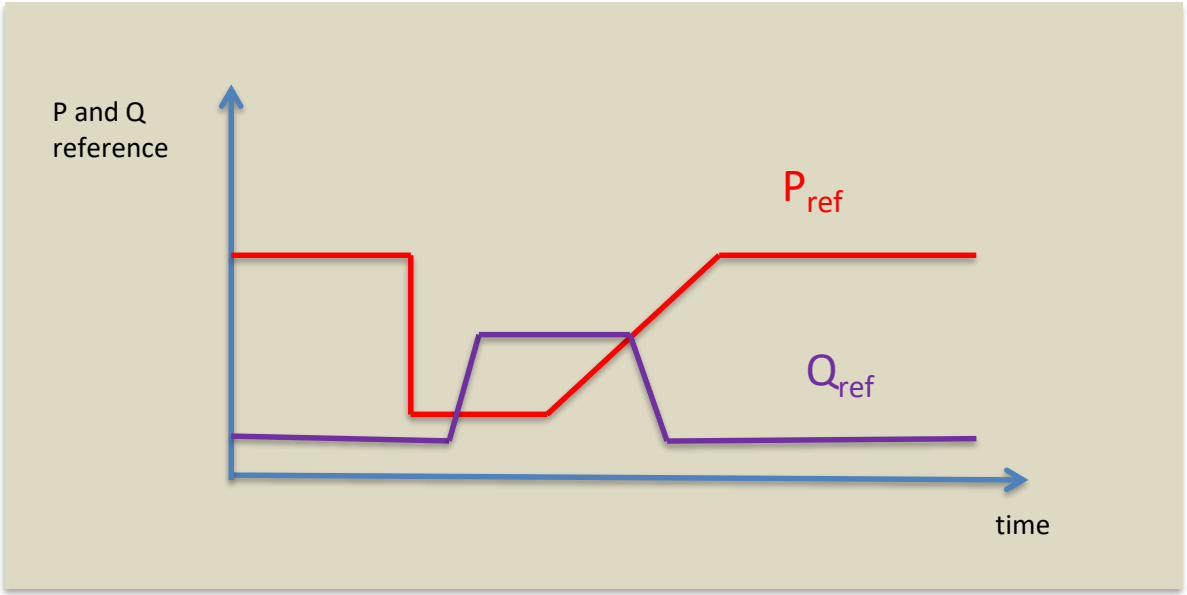




- Fault is applied at 15s for 120ms
- First 10ms duration fault: large rotation in Vd and Vq frame leads to high Iq injection and Low Id injection
- Next 50ms, inverter bring down Id and Iq to allow the PLL to relock to the phase
- Last 60ms during the fault: inject Iq to support the system
- After fault release, PLL goes unstable and causes large voltage fluctuation

Multiple inverter based generation and dynamic reactive power compensation devices connected in a weak grid area – Control interaction and coordination problem

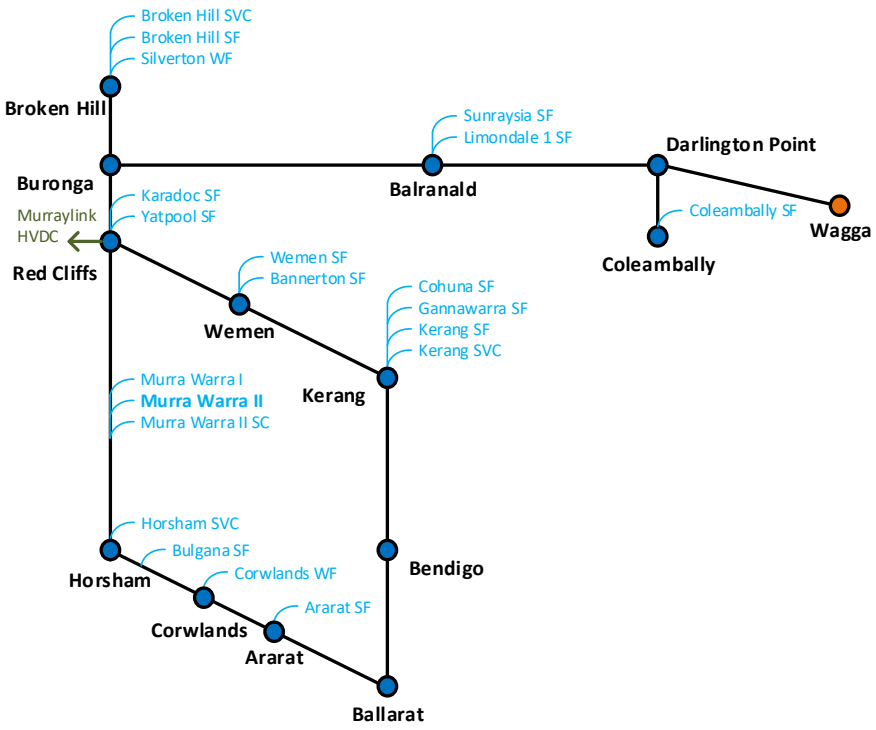
- Power and reactive power ramp rate following fault clearance are key parameters that can lead to 'interactions' – specially under weak grid conditions
    - **Power restore requirement upon fault**; 'Typical' requirement is 95% power within 100 ms
    - Maybe negotiated with TSO
- SRC was approximately 1.5 – 2

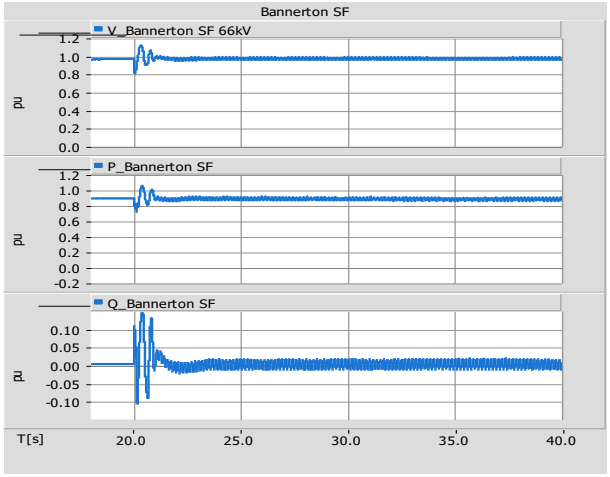


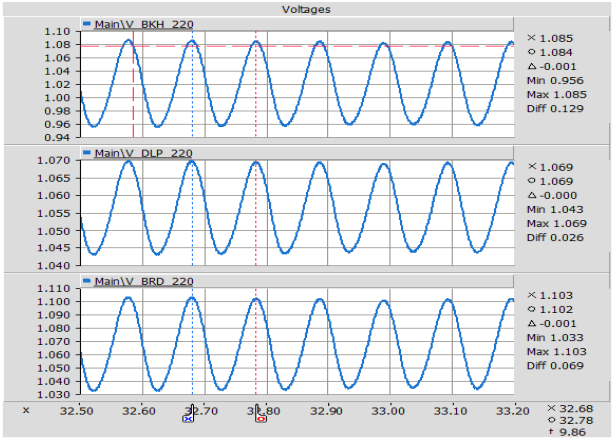
Example 4 – Low Frequency Voltage Oscillations – Weak Grid Issue

Example 2 – Low Frequency Voltage Oscillations (8- 10 Hz range)

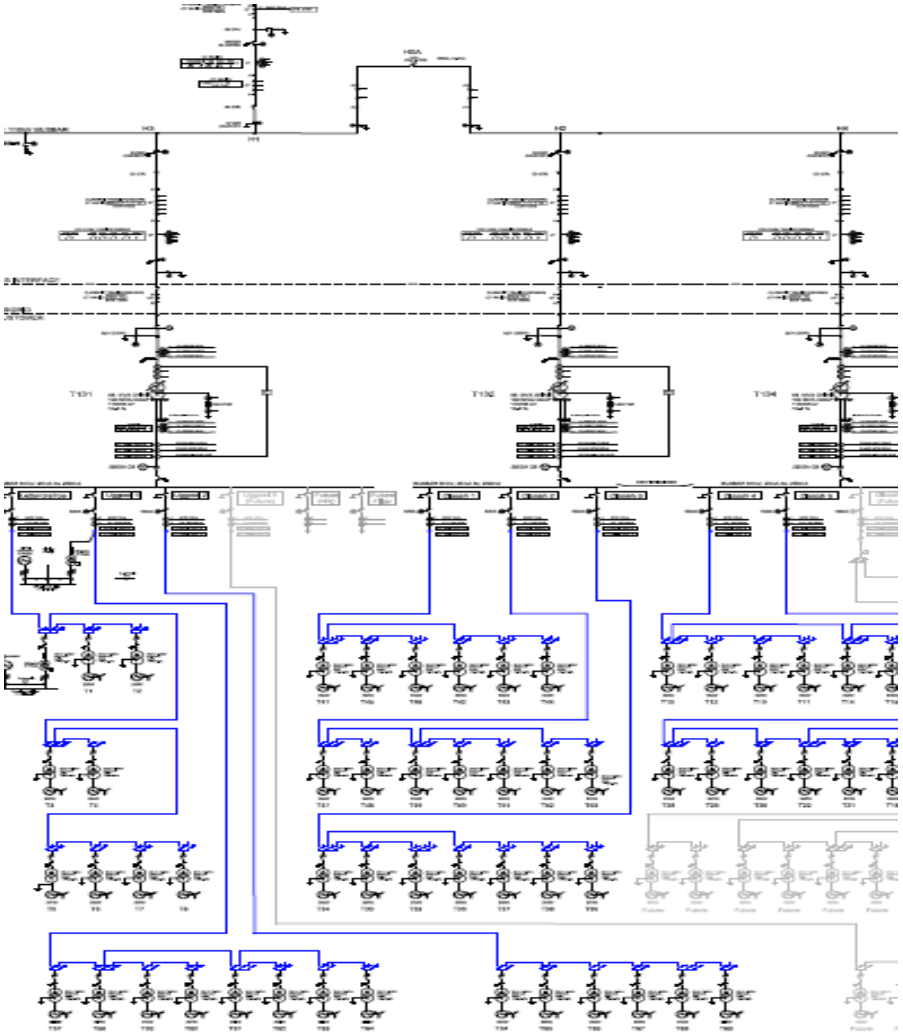
Low Frequency Voltage Oscillations – Interaction between multiple dynamic devices





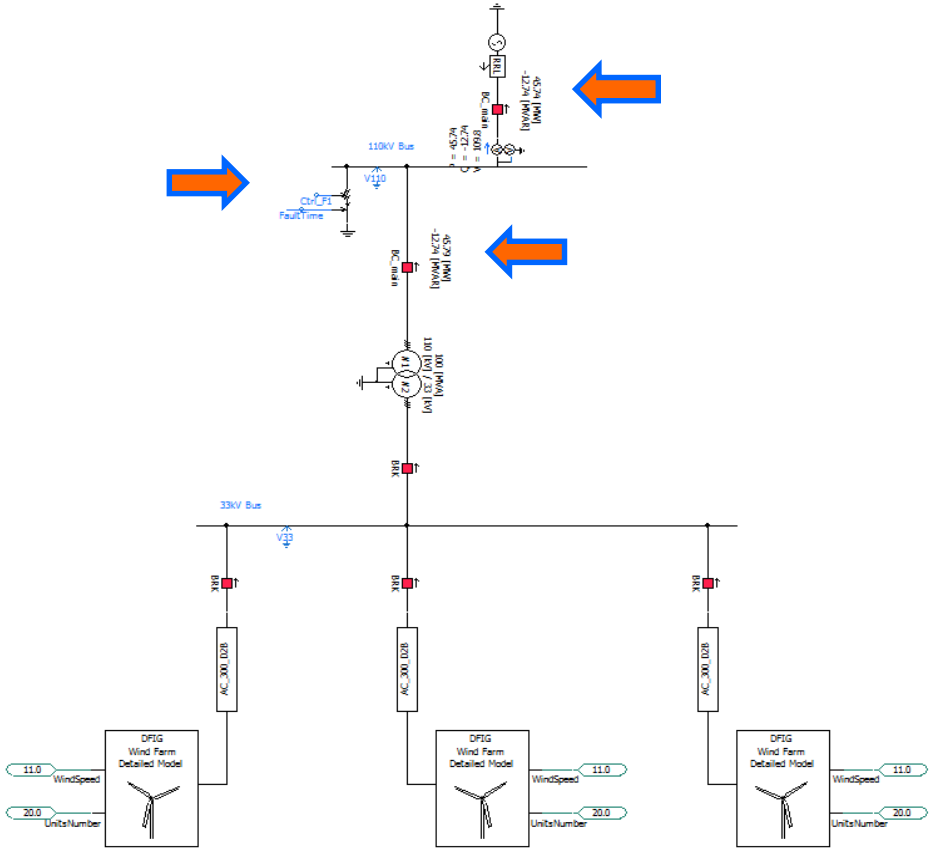


Example 5 – Faults on Collector system



Study Model – Temporary Over voltages (TOV)

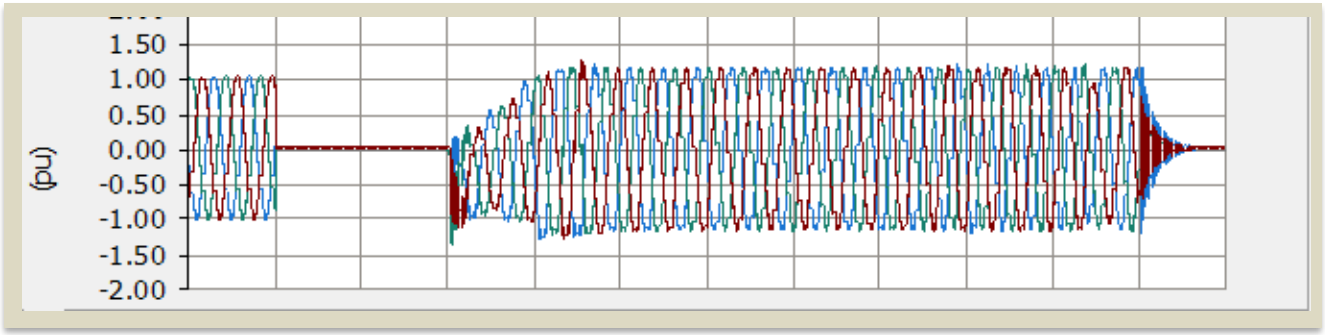
- Wind farm and collector system connected to the power grid
- Breakers opened due to a fault on the ac network
  - Breakers isolate the wind turbines (WTs) and the cables from the grid
  - Rapid increase of the collector network and terminal voltages of WTs



TOV on Isolated Collector Feeders

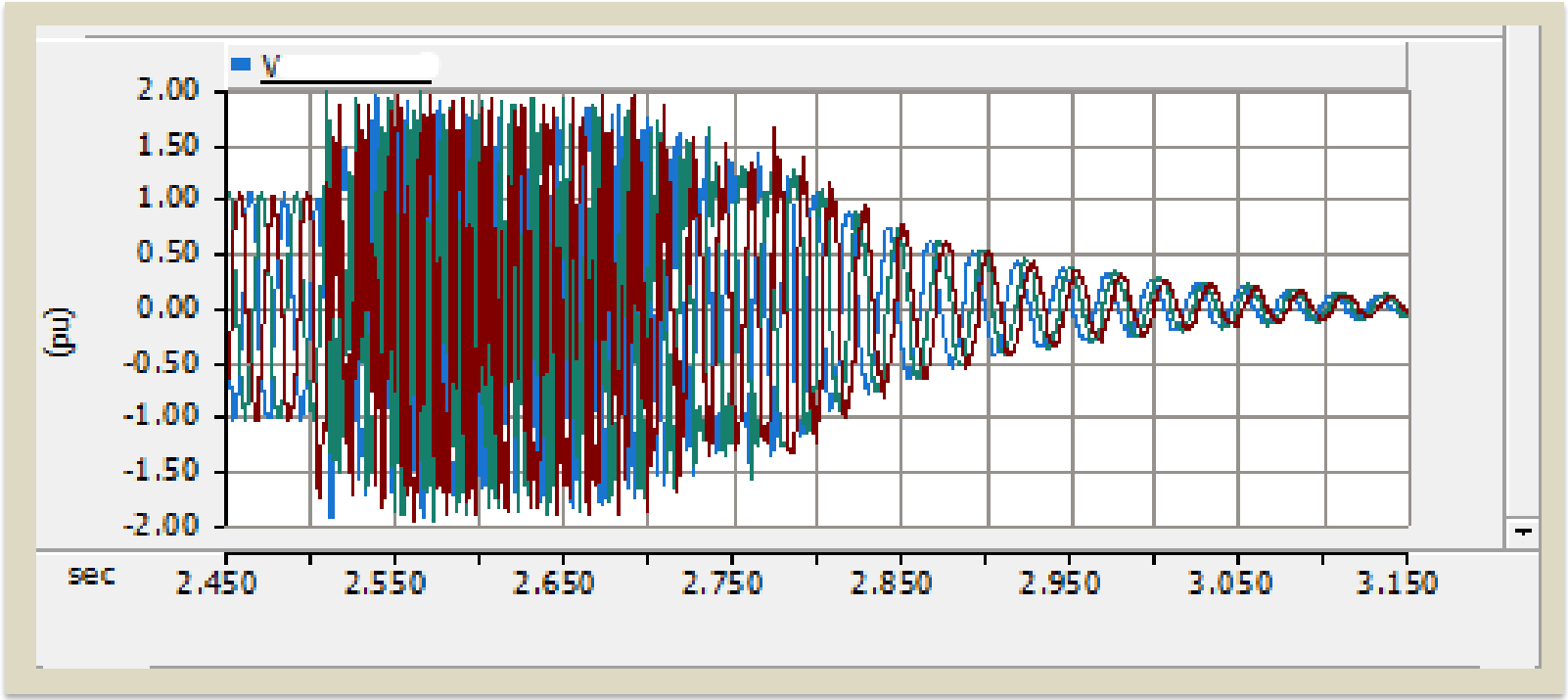
Rapid increase of the collector network and terminal voltages of WTs

- Serious TOV concern
- WTGs should be able to limit this TOV through protection and control action
- Cable capacitance and number of tripped WTG units effect TOV

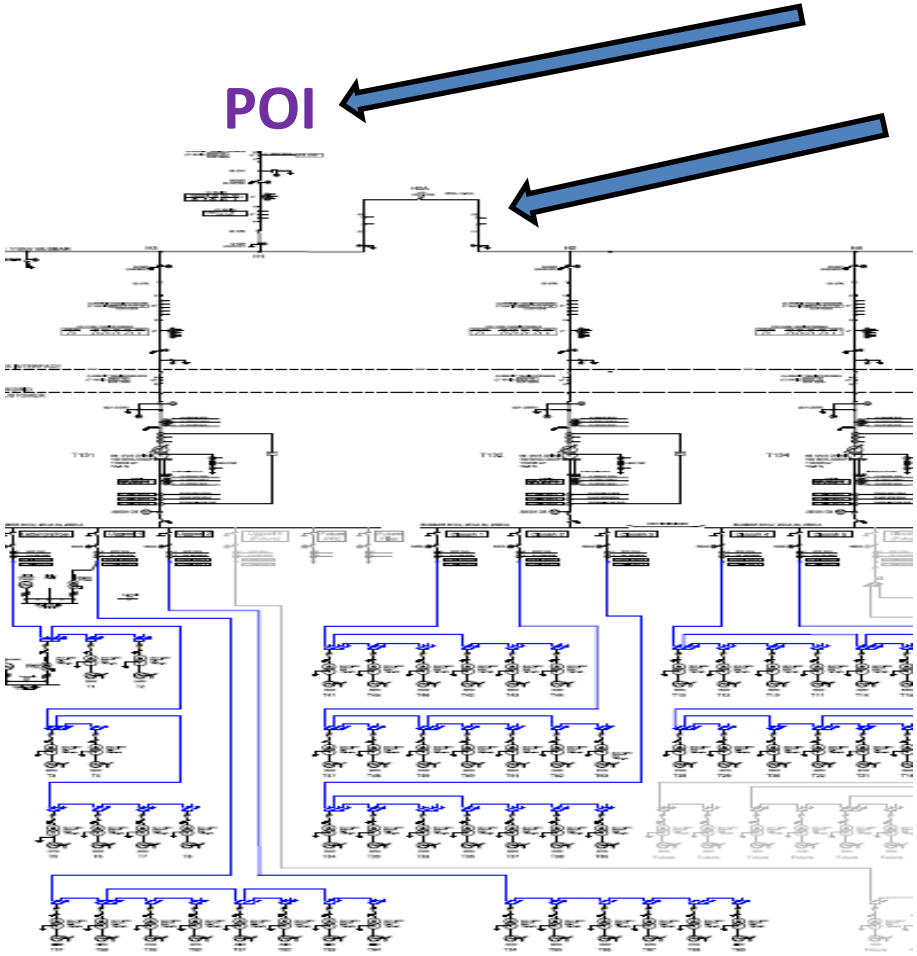


TOV on Isolated Collector Feeders

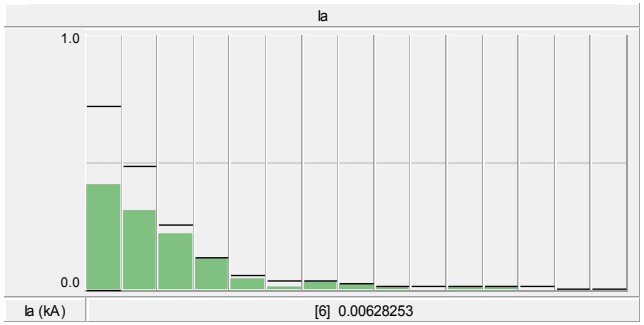
Fault on the 110 kV side



Example 6 – Harmonic Performance

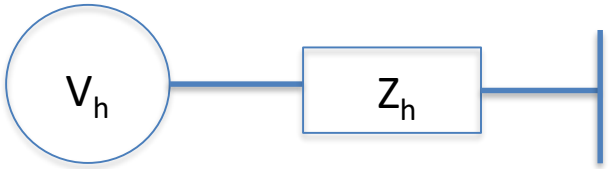


What are the harmonic impact at POI and customer load locations (THD).



Harmonics injected from the converter based wind (or PV) penetrated to the POI and utility network via the array cables or lines.

Harmonic Model of a WTG



The simplified harmonic source parameters are derived based on detailed EMT model response and (potentially) validated through field measurements

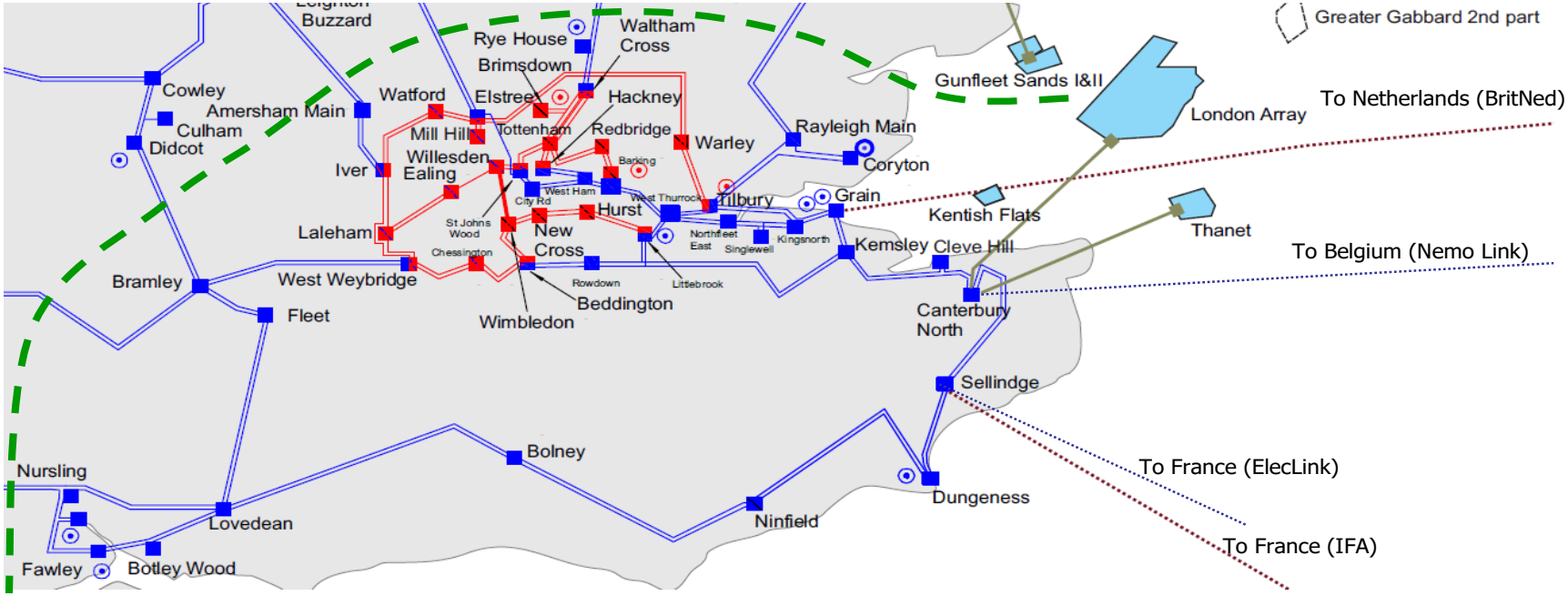
V_h - Harmonic voltage source

Z_h - Harmonic impedance (frequency dependent)

Example 7: – Control Interaction and SSTI Impacts - South East England

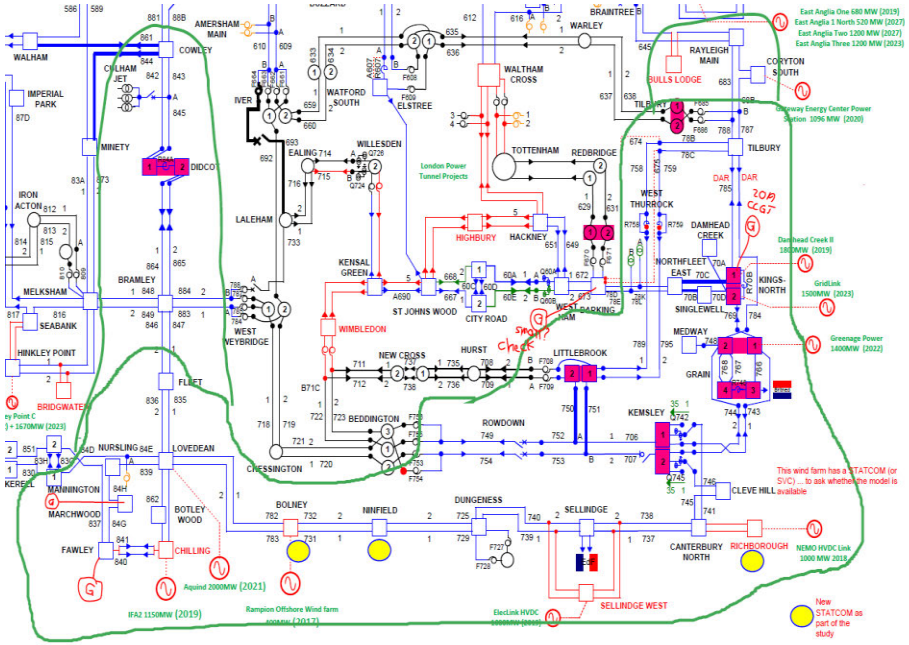
Potential Control Interaction and SSTI Issues - South East England

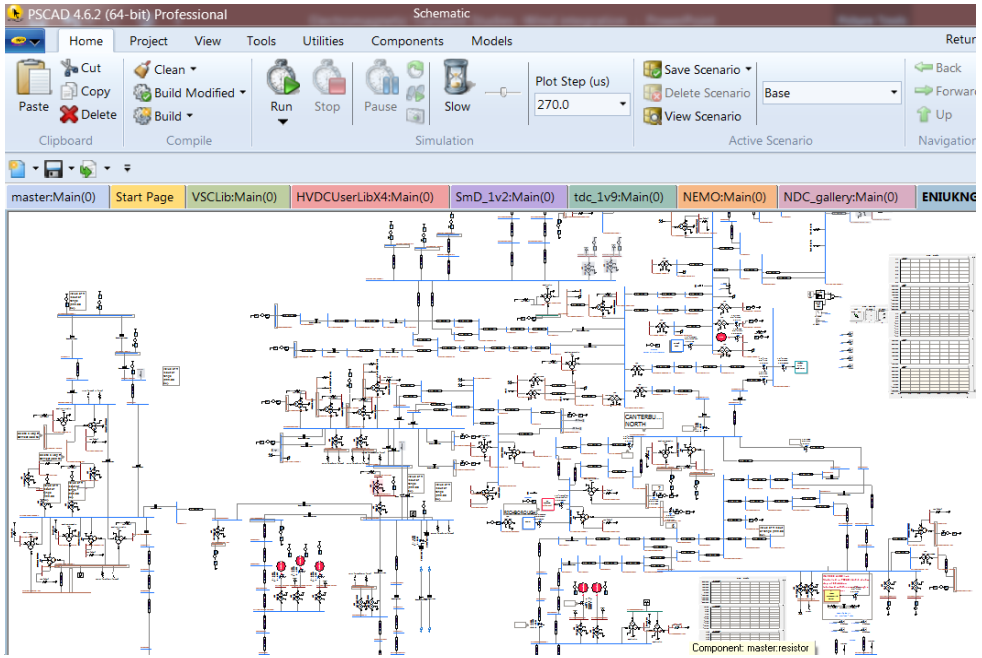
- South East England is where several HVDC interconnectors land and is a region that has little synchronous plants and even that is being displaced by offshore wind farms.
- Three STATCOMs commissioned to provide voltage support.
- The short circuit ratio is low and reactive current during a fault is sought.
- Control interactions and sub synchronous oscillations concerns given the 'weak grid'.



Potential Control Interaction and SSTI Issues - South East England

- Modelling the entire South East England network including all vendor models for all HVDC, STATCOMS, Wind farms in EMT Platforms.





Model Validation of South East England between PSCAD and PF

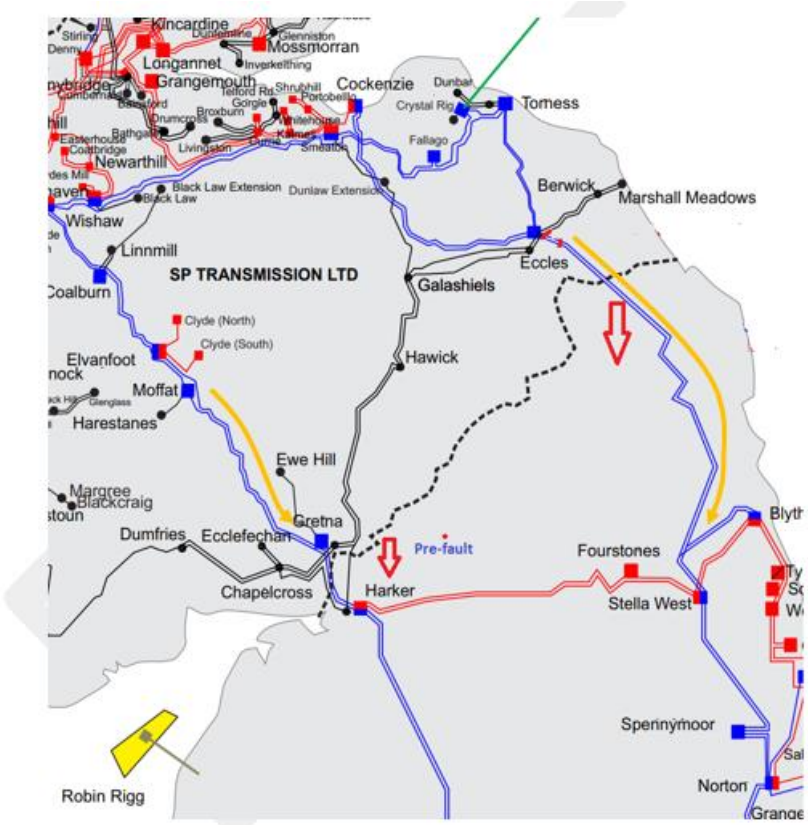
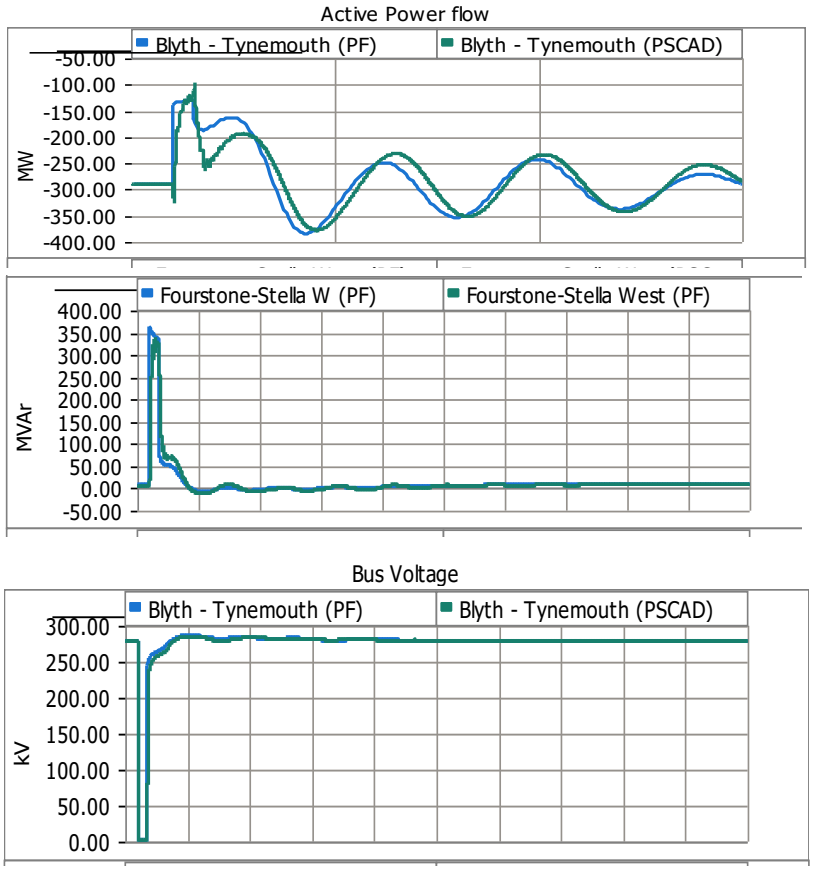


Figure 1: Two 400kV transmission corridors from Scotland to England



The PSCAD model was validated against dynamic response results of the full National Grid System model in Power Factory.

Thank You

Manitoba
HYDRO INTERNATIONAL